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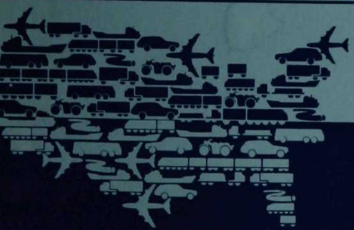
ANL/EES-TM-310

COST ANALYSIS OF PARTICULATE EMISSION CONTROL TECHNOLOGY FOR HEAVY-DUTY DIESEL VEHICLES



Center for Transportation Research

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by

John Rajan* and Margaret K. Singh

Energy and Environmental Systems Division
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ABSTRACT

New particulate emission standards for heavy-duty diesel engines require the use of particulate traps in heavy-duty diesel vehicles by 1991. The viability and cost of such traps is a subject of disagreement between the U.S. Environmental Protection Agency (EPA) and manufacturers of trucks, buses, and engines. This study discusses particulate trap-oxidizer technology and available cost estimates, the basis of their derivation, and the reasons for their differences. Particular focus is placed on the EPA estimates, about which several tentative conclusions were reached. First, EPA does not account for trap assembly costs or potential vehicle modification in its total-cost estimates. Second, EPA's allowance for research and development costs appears low. Third, EPA's allowance for manufacturer's markup may be limited, particularly if the markup is to cover warranty, recalls, and marketing. Fourth, EPA does not assume that trap replacement will be required during the life of the vehicles; however, other analyses suggest that trap life may be shorter than estimated by EPA. Fifth, EPA's allowance for fuel economy impact is lower than that of other estimates. The report concludes that EPA life-cycle cost estimates for heavy-duty vehicle particulate traps are the lowest estimates possible and may be realized only if all of EPA's assumptions are valid.

1 INTRODUCTION

A previous report by Argonne National Laboratory (ANL) identified a significant disagreement between the U.S. Environmental Protection Agency (EPA) and manufacturers of heavy-duty diesel engines and trucks (HDDEs and HDDTs, respectively) over the cost of implementing particulate control in HDDTs.[1] The EPA estimated that the retail prices of HDDTs would increase by approximately \$527 to \$650 (1980 dollars) as a result of engine and vehicle modifications (e.g., particulate trap-oxidizer systems, which collect particulates from diesel engine exhaust and periodically burn them to restore trap efficiency) necessitated by the proposed particulate standard of 0.25 grams per brake horsepower-hour (g/bhp-hr).[2,3] Several manufacturers suggested that the cost of particulate trap-oxidizer systems would increase prices from \$2000 to \$3500 (1982 dollars).[4,5] Further, EPA estimated that fuel economy would not be affected by these systems and that vehicle maintenance costs would be reduced. The manufacturers expected a 1% to 2% penalty in fuel economy with trap-oxidizers and considerable additional maintenance.

Based on subsequent analysis it conducted, EPA revised its cost estimates for particulate control, with emphasis on particulate trap-oxidizers.[6-8] However, as discussed in this report, a large difference in estimated costs still exists between EPA and the manufacturers: EPA projects that hardware costs (i.e., the trap-oxidizer systems) will range from $150 to $598 (1984 dollars) per vehicle, depending on trap type and vehicle size.[8] Manufacturers' cost estimates range from $575 to $7210 per vehicle.[8]

The original purpose of this study was to examine the reasons for these large differences in estimated costs. Ideally, cost differences for hardware, research and development, maintenance, and fuel economy should be examined. The EPA is generally quite explicit in stating its assumptions about these costs. On the other hand, the manufacturers have not provided much cost detail with which to make comparisons. However, Energy and Resource Consultants, Inc. (ERC), an EPA subcontractor, has also assessed particulate control costs.[9] The ERC assessment was developed in part from discussions with, and review by, manufacturers of HDDEs and particulate control devices. Cost estimates made by ERC are higher than those of EPA. This study focuses on a comparison of the most recent EPA cost estimates with those of ERC and incorporates the manufacturers' estimates where available. The purpose of this study is to explain and discuss, where possible, the reasons for the differences among the various cost estimates.

2 CLASSIFICATION OF HEAVY-DUTY VEHICLES AND ENGINES

As defined by EPA, heavy-duty vehicles (HDVs) are highway vehicles with a manufacturer's gross vehicle weight (GVW) greater than 8500 lb. Table 1 lists manufacturer's weight classes; the HDVs are Classes 2B through 8.

These individual classes can be aggregated in several ways, and the two reports upon which this analysis primarily draws did so in different fashions.[8,9] Thus, some caution is required when comparing the analysis of these two reports. The EPA, in its 1985 Regulatory Impact Analysis, placed HDDEs in three categories: those used primarily in Classes 2B through 5 are light HDDEs, those used primarily in Classes 7 and 8 are heavy HDDEs, and those used in transit buses are considered to be medium HDDEs.[8] Energy and Resource Consultants, Inc., has categorized heavy-duty diesel vehicles as (1) light-heavy trucks, which include trucks of 8500 to 14,000 lb GVW (or Classes 2B and 3); (2) medium-heavy trucks, which include trucks of 14,001 lb GVW and over, but apparently no more than 50,000 lb (or Classes 4 through 8); and (3) line haul trucks, which include all trucks of 50,000 lb GVW or more.[8] Transit buses are treated as a separate class.

The EPA also categorizes these vehicles in one other way that should be discussed. Three useful-life HDDE subclasses were established in a Nov. 16, 1983, rulemaking on hydrocarbon (HC) and carbon monoxide (CO) standards.[10] According to the regulations, engines are to be categorized as light, medium, or heavy HDDE, depending on the primary use for which the engine is designed and marketed. Gross vehicle weight, vehicle usage, and operating patterns are to be considered in the designation. Engines in the light HDDE category are expected to be used normally in vehicles with a maximum GVW of 19,500 lb (Classes 2B through 5), engines in the medium HDDE category are typically used in vehicles of 19,500 to 33,000 lb GVW (Classes 6 and 7), and engines in the heavy HDDE category are typically used in vehicles above 33,000 lb GVW (Class 8). These are the classifications that EPA will use in its averaging programs for nitrogen oxides (NO_x) and particulates (briefly discussed in Sec. 3).

TABLE 1 Manufacturer's Weight Classes for Trucks

Class	Gross Vehicle Weight (lb)
1	<6,000
2A	6,001-8,500
2B	8,501-10,000
3	10,001-14,000
4	14,001-16,000
5	16,001-19,500
6	19,501-26,000
7	26,001-33,000
8	≥33,001

3 EMISSION STANDARDS

Section 202(a)(3)(A)(iii) of the Clean Air Act (CAA), as amended in 1977, called for particulate emission standards after model year 1981 that reflect

> ...the greatest degree of emission reduction achievable through the application of technology which the Administration determines will be available for the model year to which such standards apply, giving appropriate considerations to the cost...

On January 7, 1981, EPA issued a Notice of Proposed Rulemaking (NPRM) that stipulated a particulate standard of 0.25 g/bhp-hr for HDDEs to take effect in 1986.[3] This proposed standard, along with others for NO_x, HC, and CO for all heavy-duty engines, was under review for several years. On Oct. 15, 1984, EPA published a second NPRM that covered particulates, but also included NO_x standards for light-duty trucks and heavy-duty engines.[11] On March 15, 1985, EPA issued its final rule on particulate and NO_x standards for heavy-duty engines (as well as NO_x standards for light-duty trucks).[12]

Table 2 shows the present and future emission standards for HDDEs. Emissions averaging within specific truck service classes is permitted beginning in 1991. The production-weighted particulate emission level of each subclass of trucks (light, medium, and heavy) of a given manufacturer must be at or below 0.25 g/bhp-hr in 1991 and 0.1 g/bhp-hr in 1994. Individual families within each subclass may be higher, but no more than 0.6 g/bhp-hr.

It is generally agreed that particulate trap-oxidizers will be required to meet the 1991 and 1994 standards.[8,9] From the comments it received from manufacturers, the EPA concluded that the approximate lower limit for a nontrap-based particulate standard would be 0.5 g/bhp-hr.[8]

Particulate emissions are not a concern with heavy-duty gasoline engines (HDGEs) except for lead-related emissions, which are related more to fuel than to engine design; thus, the particulate standards do not apply to them. Emission standards applicable to HDGEs are shown in Table 3.

TABLE 2 Federal Emission Standards for Heavy-Duty Diesel Engines[a]

	Exhaust Emissions (g/bhp-hr)[b]				
Year	HC	CO	NO_x	Particulates	Smoke[c]
1985-1987	1.3	15.5	10.7	-	Accel. 20, Lug 15, Peak 50
1988-1990	1.3	15.5	6.0	0.6	Accel. 20, Lug 15, Peak 50
1991-1993	1.3	15.5	5.0[d]	0.25[e] (truck) 0.1 (transit bus)	Accel. 20, Lug 15, Peak 50
1994 and later	1.3	15.5	5.0[d]	0.1 (truck)[e] 0.1 (transit bus)	Accel. 20, Lug 15, Peak 50

[a]Additional requirements: No crankcase emissions are permitted starting in 1984. This requirement does not apply to turbocharged engines or engines whose intake air is inducted solely by pumps, blowers, or superchargers.

[b]Emissions are determined by the EPA transient test procedure.

[c]Smoke limits are based on a special cycle. The numbers are percent opacity limits for three conditions: acceleration, lug, and peak.

[d]Emissions averaging of engines within a given primary service class is permitted. Individual engine families may not exceed 6.0 g/bhp-hr NO_x.

[e]Emissions averaging of engines within a given primary service class is permitted. Individual engine families may not exceed 0.6 g/bhp-hr particulates.

TABLE 3 Federal Emission Standards for Heavy-Duty Gasoline Engines[a]

Year	Test Procedure	Gross Vehicle Weight[b] (lb)	Exhaust Emissions (g/bhp-hr) HC	CO	NO_x
1985-1986	MVMA[c] transient	-	1.9	37.1	10.6
	or				
	EPA transient	-	2.5	40.0	10.7
1987	MVMA transient	≤14,000[d]	1.1	14.4	10.6
		>14,000	1.9	37.1	10.6
1988-1990	MVMA transient	≤14,000[d]	1.1	14.4	6.0
		>14,000[d]	1.9	37.1	6.0
1991 and later	MVMA transient	≤14,000[d]	1.1	14.4	5.0[e]
		>14,000	1.9	37.1	5.0[e]

[a]Additional requirements: (1) No crankcase emissions are permitted; (2) CO standard of 0.50% at idle is established for 1987 and later model years (applies only to those engines using after-treatment technology for 1987 and later); (3) evaporative emissions standards took effect in 1985 (they are 3.9 g/test for trucks ≤14,000 lb GVW, and 4.0 g/test for trucks >14,000 lb GVW [does not apply to model year 1985 heavy-duty trucks with 1984 heavy-duty engines]).

[b]In 1987 and later, engine emission standards vary with GVW of the truck in which the engines are intended to be used.

[c]MVMA = Motor Vehicle Manufacturers Association.

[d]A manufacturer may certify up to 5% of its engines for use in trucks ≤14,000 lb to the standards applicable to trucks >14,000 lb.

[e]Emissions averaging permitted. Individual engine families may not exceed 6.0 g/bhp-hr NO_x.

4 PARTICULATE TRAP-OXIDIZER TECHNOLOGY

4.1 DEVELOPMENT STATUS

4.1.1 Light-Duty Systems

Research and development (R&D) on particulate trap-oxidizers by the light-duty diesel vehicle industry is aimed at meeting federal and California light-duty diesel vehicle (LDDV) particulate emission standards, which in effect require particulate trap-oxidizers in 1987 (federal) and 1985 or 1986 (California), respectively. The EPA believes that trap-oxidizer technology for light-duty diesels is at a very advanced stage of development.[7] This conclusion appears justified by the fact that Mercedes Benz certified a 3-liter turbodiesel equipped with a trap-oxidizer to meet the California 1985 model year LDDV particulate standards.[7] Further, Volkswagen (VW) has announced plans to install trap-oxidizers on some of its California 1986 model year LDDVs (Quantums) and to equip all diesel Quantums with particulate trap-oxidizers for compliance with the 1987 federal LDDV particulate regulations.[7]

However, EPA's characterization of LDDV trap-oxidizer technology as "very advanced" is not universally accepted. For example, General Motors (GM) maintains that the currently available technology is inadequate to meet the 1987 EPA standards for light-duty diesel trucks (LDDTs).[8] General Motors has conducted a sizable LDDT testing program (200 alternate fuels and fuel additives combined with more than 150 trap materials in more than 500 traps), but has not been able to identify to its satisfaction a light-duty trap-oxidizer that could be committed to a production program.

4.1.2 Heavy-Duty Systems

The EPA believes that the trap-oxidizer technology under development for LDDVs can be adapted for heavy-duty diesel vehicles (HDDVs).[8] However, EPA recognizes that specific differences between light- and heavy-duty applications must be considered in designing the trap-oxidizer systems. For example, HDDVs have a higher exhaust volume and mass flow rate, thus increasing the amount of particulate in the exhaust. To compensate for the increased flow rate, the heavy-duty trap must be large enough to ensure that exhaust gas back pressure (due to the collected particles clogging the trap's passageways) does not rise too quickly or that regeneration does not occur too frequently (regeneration is the process of oxidizing, or burning off, of the particulate matter trapped in a filter, thus restoring the filter to "clean-trap" efficiency). This larger trap volume can be achieved with either larger traps or multiple traps. Further, most currently produced HDDVs are turbocharged and consequently have lower exhaust temperatures than LDDVs. As a result, the temperature necessary for regeneration may not be achieved as readily as in a LDDV. Also, the useful life of HDDVs is greater than that of LDDVs (110,000 to 290,000 miles vs. 100,000 miles), requiring greater durability in the HDDV traps (actual life of HDDVs can be much greater).

Current design efforts are aimed at a suitable regeneration system that can treat the larger volumes of exhaust gases from HDDVs and operate effectively in the lower exhaust temperatures of turbocharged engines. The greatest design challenge with the heavy-duty system is durability over the life of the vehicle under varied operating conditions. The HDDV manufacturers have expressed numerous concerns about development of trap-oxidizers by 1990-1992.[13] For example, after two years of testing, International Harvester is particularly concerned about trap-oxidizer durability. Mack is also concerned about trap durability, although it has indicated that regeneration and its control appear to be feasible. Caterpillar does not see as practical the availability of traps for the 1990 model year, but makes no mention of possible implementation dates. General Motors has expressed concern about meeting particulate standards for 1990-1991. Cummins does not envision its use of traps by 1992.

Volvo White indicated that qualified traps may be available by 1991 if the sulfur content of diesel fuels could be controlled. Daimler Benz, however, was the only manufacturer that indicated the 0.25 g/bhp-hr trap-based standard for the 1990 model year *would* be possible, contingent on the availability of low-sulfur fuels. Further, Daimler Benz recommends a standard for line-haul trucks that does not require trap-oxidizers. While Daimler Benz has demonstrated the maximum development in the HDDV trap program, much more development work on regeneration of its wound-ceramic-fiber trap is needed to ensure acceptable durability. In current tests in urban buses, these traps have demonstrated a life of 100,000 to 150,000 miles, but even greater durability is needed.

4.2 TYPES OF PARTICULATE TRAPS

A number of different traps are under development for HDDVs. They include the ceramic monolith trap, ceramic fiber trap, and catalyzed wire mesh trap; each is described briefly below.

4.2.1 Ceramic Monolith Trap

The most widely tested and developed type of particulate trap is the ceramic monolith trap, which is diagrammed in Fig. 1. In this trap, the ceramic monolith material is constructed as a matrix of alternately opened and closed cells. Particulates are collected in the cells as the exhaust flows through the porous wall of one cell into the next. The monoliths made for the HDDVs are assumed by EPA to be 12 inches in diameter, although smaller ones could be made. The significant advantages of this system are a high trapping efficiency, tolerance to varying temperatures, demonstrated durability, and relatively low cost. Other advantages include adaptability (e.g., variation of wall thickness and porosity) to allow tradeoffs between back pressure and filtration efficiency, and the ease with which it may be coated or impregnated with metallic catalysts for regeneration (the regeneration process is discussed in Sec. 4.4). Drawbacks include high back pressure, rapid increase in back pressure with particulate loading, susceptibility to thermal-stress-induced cracking, and possible clogging due to ash retention. However, the ability of this system to retain particulates increases over time because the particulate matter lodged in the walls tends to enhance its efficiency.

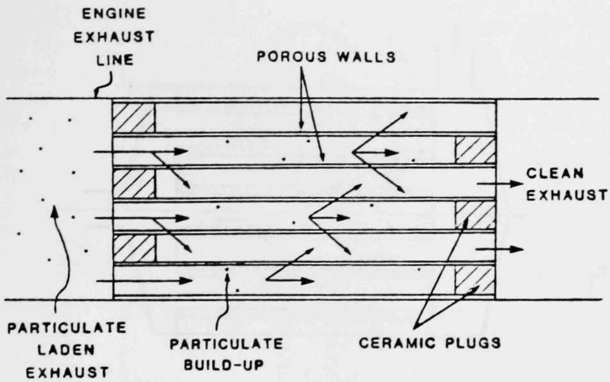


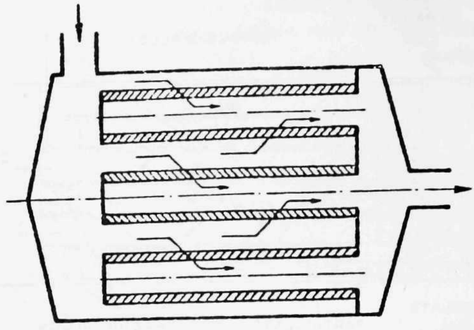
FIGURE 1 Ceramic Monolith Trap (Source: Ref. 9)

The problem of a long-term increase in back pressure due to ash buildup was identified in simulations by Cummins and in actual operation by Daimler Benz. The Cummins simulations identified a doubling of back pressure after approximately 56,000 miles. Daimler Benz identified ash buildup and resultant plugging after 100,000 to 150,000 miles. However, in an EPA-sponsored durability test, Southwest Research Institute (SwRI) detected only a 20% increase in back pressure over 50,000 miles of operation. Tests with metallic fuel additives have shown extensive accumulation of metallic ash without significant changes in back pressure. Volkswagen has independently reported similar results. These results may be due to the lower temperatures of catalytic regeneration or because the composition of the ash formed in the VW and SwRI tests produced a lower increase in back pressure. Overall, heavy-duty ceramic monolith traps may need replacement at about 150,000 to 200,000 miles, but this must be verified by further R&D.[9]

4.2.2 Ceramic Fiber Trap

Although this type of trap has been evaluated by several manufacturers, little information is available. Caterpillar's report on testing a trap using "ceramic yarn" provides scant information, as there appears to be difficulty in developing a space-efficient support for the yarn.[9] Results of GM's tests on ceramic fiber mat or felt traps have not been encouraging. The main failure modes experienced by GM and Daimler Benz have included mat disintegration and cracking, as well as separation of the mat from its support.

Daimler Benz has developed a different and more promising type of trap based on ceramic fibers. Using strands of silica-fiber yarn cross-wound on a porous metal substrate, they produce cylinders called "candles." These are assembled in a canister so that the exhaust gases must flow through the candle walls to escape (Fig. 2). The silica fibers are roughened and impregnated with a heat-resistant inorganic substance to improve filtration.



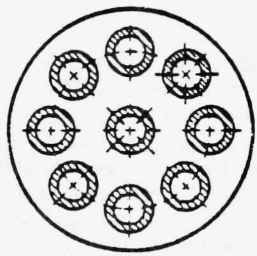


FIGURE 2 Daimler-Benz Silica-Fiber Candle Trap (Source: Ref. 9)

Daimler Benz has reported efficiencies exceeding 90% with this trap and back pressures below those of the ceramic monolith. Tests on HDVs have demonstrated a life of at least 125,000 miles. In the demanding transit bus application, the demonstrated range of life has been 100,000 to 150,000 miles. The main failures are caused by the high sulfur content of fuel, which results in trap plugging by noncombustible ash and unacceptable increases in back pressure. Amenable to catalytic regeneration, this trap appears almost ideal. However, its large size may be a drawback.

4.2.3 Catalytic Radial-Flow Wire Mesh Trap

Johnson-Matthey, Inc., has developed and produced this type of trap. Consisting of cylindrical sections of knit stainless steel mesh, with the density of the mesh increasing toward the center of the section, the system usually replaces the exhaust manifold in LDDVs (Fig. 3). In heavy-duty designs, the lengths and numbers of cylinders are varied and the trap is usually located under the floor. The mesh is coated with alumina to which a precious-metal catalyst is applied. The exhaust gas flows inward

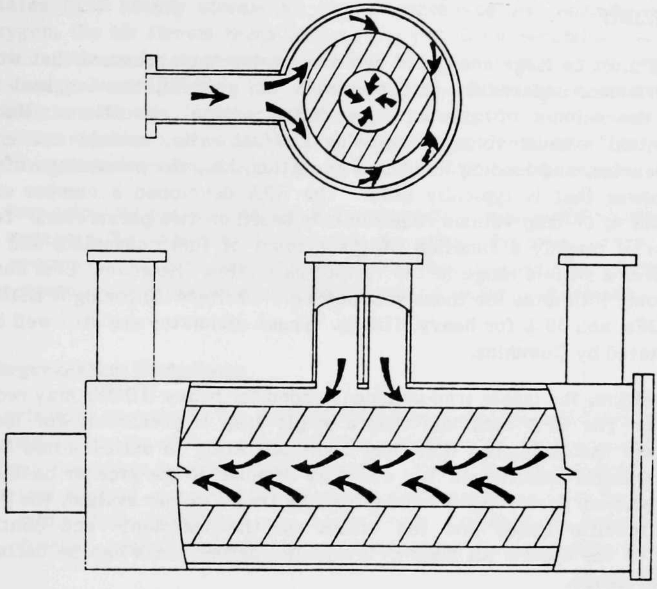


FIGURE 3 Catalytic Radial-Flow Wire Mesh Trap in Engine Manifold (Source: Ref. 9)

through the walls of the cylinder and leaves the trap through the center. The higher density toward the center of the trap ensures that a thick layer of particulate matter is not formed at the periphery.

The catalyst coating is the main component in the system. Besides oxidizing HC and CO, the catalyst ensures the reduction of odorous emissions and the oxidation of a major portion of the HC fraction of the particulate material. More important, the catalyst reduces the light-off (ignition) temperature of the trapped particulates from about 500-600°C to about 350-400°C, reducing the energy required for regeneration.

Some advantages of this trap over the monolith are the slightly lower increase in back pressure, which also occurs at a lower rate and which may be even further reduced by self-regeneration, particularly in heavy-duty service. Moreover, the stainless steel mesh is not susceptible to thermal cracking. Thus regeneration and its control are simplified. Disadvantages of the system are its higher cost, lower efficiency, and tendency to increase sulfate emissions. The higher initial cost may be offset by the simpler regeneration process and lower associated maintenance cost. Efficiencies in test vehicles have ranged from 50% to 80%, adequate to meet the 0.25-g/bhp-hr standard. Increased sulfate emissions, however, are a major drawback.

4.3 TRAP SIZING

Traps must be large enough to avoid excessive back pressure that would degrade engine performance and reduce fuel economy. In general, the required trap volume depends on the volume of exhaust flow during normal operation. Many variables determine actual exhaust volume, including air/fuel ratio, vehicle and engine speed, engine efficiencies, and loading in normal operation, i.e., the percentage of the engine's rated horsepower that is typically used. The EPA developed a number of estimates, shown in Table 4, of trap volume requirements based on two parameters: fuel economy (exhaust flow is roughly a function of the amount of fuel consumed) and horsepower. Clearly there is a sizable range in the various estimates. However, EPA concluded that reasonable point estimates for these volumes were 11 liters (L) for light HDDEs, 21 L for medium HDDEs, and 39 L for heavy HDDEs. These estimates are still well below the 60 to 90 L estimated by Cummins.

In addition, the larger trap volumes needed for heavy HDDEs may require the use of two traps. The EPA considers that a single trap is preferable for most systems. General Motors has suggested that dual traps operating in series would be useful but would cause a slight sacrifice in fuel economy because of the greater back pressure. In effect, the optimum performance in each vehicle trap-oxidizer system, the geometry and location of specific traps, and the effect on the transient- and continuous-cycle performance of the system all must be evaluated before costs can be defined with any degree of confidence.

4.4 REGENERATION TECHNIQUES

Regeneration of traps to restore them to "clean-trap" efficiency and back pressure is usually achieved by oxidizing the particulates, i.e., raising the temperature of

TABLE 4 Summary of EPA Trap Volume Estimates for Heavy-Duty Diesel Engines

HDDE Category[a]	Estimated Average Fuel Economy (mpg)	Estimated Average Horsepower	Volume Based on Fuel Economy Factor (L)	Volume Based on Horsepower Factors (L): Horsepower Factor Derived from Light HDDE (EPA test)	Horsepower Factor Derived from Medium HDDE (EPA test)	Horsepower Factor Derived from Medium HDDE (GM test)
Light	15.1	130	8.6	5.2	13.0	14.4
Medium	8.0	200	13.3	7.4	18.5	20.4
Heavy	5.9	350	22.0	14.0	35.0	38.5

[a]HDDE = heavy-duty diesel engine.

Source: Ref. 8.

the particulates in a steady stream of oxygen-containing gas (usually air). Besides providing oxygen, the air stream tends to keep the trap from becoming too hot, because the combustion process is exothermic. In the absence of catalysts, typical ignition temperatures range from 500°C to 600°C, with the specific temperature defined by trap design, particulate collection methods, and oxygen concentration of the air supply. To ensure complete regeneration without trap destruction from high temperatures, an adequate air flow is maintained at slightly above the ignition temperature.

The two principal approaches are self-regeneration and positive regeneration. In the former, regeneration occurs during normal operation. Positive regeneration, on the other hand, requires a definite decision to accomplish regeneration of the traps at a specific time, resulting in a series of planned sequential or parallel actions.

4.4.1 Self-Regeneration Techniques

The principal techniques for self-regeneration lower the ignition temperature for particulate oxidization by either catalytic fuel additives or catalytic coatings on the trap. The first technique is being developed for LDDVs and the additives are organometallics; metals such as copper, lead, calcium, and manganese have been or are being evaluated. While this technique has been found satisfactory in some light-duty applications, further evaluation may be needed before its application to heavy-duty vehicles.

Failure modes in the additive/monolith traps have been thermal-stress-induced cracking of the ceramic wall and trap plugging due to accumulated additive. While the first problem may be solved by control of operating conditions, trap plugging is a serious problem not amenable to an easy solution. With a high trap-volume-to-engine-displacement ratio and lower additive concentrations, an effective trap life of 100,000 miles may be projected. In HDDTs, this could increase costs and thus be unattractive. Further, the toxicity of the organometallics may cause concern about their safety. Finally, if the additive is kept in a special reservoir, rather than being mixed with the diesel fuel, a metering system would be required.[14]

The second self-regeneration technique uses a catalyst-coated trap. Limited experiments indicate a temperature reduction of 100°C to 120°C needed to begin regeneration, and some catalysts have reduced the sensitivity of the ignition point to the partial pressure of the oxygen. While the system may be suitable for a variety of conditions, its long-term capability must be evaluated. If it proves durable and successful, this method could become the preferred approach to regeneration because of its low life-cycle cost and minimal operating problems.

4.4.2 Positive Regeneration Techniques

The most promising of the positive regeneration techniques are (1) regeneration with a diesel oil burner and (2) regeneration by HC/CO oxidation. An alternate approach suggested by EPA is electrical regeneration, in which resistance heaters provide the regeneration temperatures. Daimler Benz has also examined a positive regeneration approach for HDVs in which catalytic metal additives are injected into the exhaust stream to lower the particulate ignition temperature.

The advantages of the diesel oil burner are that it is (1) a readily available energy source with a high energy release rate and (2) a well-understood technology. The disadvantages are (1) high complexity and cost and (2) unverified durability and reliability under the hot, sooty, and highly oxidizing environment of diesel exhaust. The EPA believes that the electrical regeneration system may reduce the energy needed for regeneration; however, because this system requires an engine-driven alternator, the reduction may be marginal.

The burner and the electrical techniques can be used in either an on-line or a bypass trap-oxidizer system. The on-line system, although less complex, involves difficult control problems and possibly excessive energy use because the entire exhaust stream must be heated. Control under various engine operating conditions becomes complex, and fouling of burner and ignition surfaces by soot is common. On the other hand, bypass systems avoid the energy waste and control problems of the on-line system, but the additional components may increase costs and reduce reliability. Furthermore, evidence indicates that vehicle operation is improved when the exhaust goes through the bypass rather than the trap, thereby creating an incentive for tampering. While both systems have been evaluated in LDDVs, testing on HDDVs has been restricted to the bypass system.

Another promising positive regeneration technique applicable only to catalyst traps uses the exothermic oxidation of HC and CO to heat particulates to the light-off point. This approach may not be available for HDDVs, which have a tendency to be idled for long periods and thus have exhaust temperatures too low to initiate regeneration.[9]

A fourth technique, developed by Daimler Benz, is injection of a catalyst containing copper and chlorine into the exhaust at predetermined times. The catalyst reduces to 200°C the temperature required to oxidize the particulate; this temperature is easily attained by the exhaust stream under most operating conditions. A problem that appeared during tests was an increase in back pressure due to ash buildup in the trap. However, Daimler Benz hopes to have this system available with automatic control for the 1990 or 1991 model year.

4.5 CONTROL SYSTEMS

Both self-regenerating and positive regenerating techniques need some sort of controls. For self-regeneration, a bypass valve set to operate at a specified back pressure value, in combination with a warning light on the dashboard, may be adequate. For positive regeneration, systems for sensing, control, and actuation may be required, depending on the trap regeneration system design and vehicle/engine operation. Definition of control algorithms, while probably not the only difficult step in designing control systems, is bound to be time-consuming and expensive.

4.6 VEHICLE SYSTEM INTEGRATION

Integration of trap systems into different types of HDDVs will vary widely. The different classes of HDDVs have different body styles, power-train compositions, and usage patterns. In addition, the industry structure varies greatly between the classes. The light HDDVs tend to be more similar to the heavier LDDVs than to the large trucks with which they are grouped for regulatory purposes. Using high-speed, indirect-injected and naturally aspirated diesel engines derived from passenger car technology, they bear little resemblance to the medium-speed, direct-injected engines used in heavier trucks. Also the actual lifetime mileages of these vehicles average about 110,000 miles rather than the 270,000 to 520,000-mile lifetimes of the heavier trucks. Moreover, manufacturing processes are similar to those for LDVs and are of the mass-production type rather than the selective custom build of the heavier trucks. Given the basic similarity between the light HDDVs and LDVs, together with the assumption that trap-oxidizers will be available in LDVs in 1987, integration of traps into the light HDDTs should require comparatively little additional effort.

Medium HDDVs encompass a variety of vehicles with GVWs from 10,000 to 50,000 lb. Body styles are quite varied and include dump trucks, garbage trucks, tow trucks, and the "box" van. There are many combinations of truck chassis, engine bodies, and special equipment. Operating patterns vary extensively, although operations are basically urban. Nonetheless, a majority of these trucks are built along similar lines and with similar exhaust system layouts.[9] A generic trap-oxidizer system for this category may be possible, but it would probably require a positive regeneration system specific to the driving profile of the vehicle. Also, because these vehicles are less susceptible than LDDVs to model changes, the R&D and engineering capability of the medium HDDV manufacturers is more limited, and the introduction of variations may take longer than for the LDVs.

Line-haul trucks, usually the largest and most powerful trucks, are used primarily for intercity transportation. They require high-power turbocharged engines that have high exhaust flow rates. Very large or multiple traps would therefore be required to keep back pressure low; this is particularly important because of the long distances traveled by these vehicles and the negative effect of high back pressures on fuel economy. The great economic effect of small changes in fuel efficiency could lead to extensive tampering with emission control devices in these vehicles. Trap development time for these trucks may be longer than that for the medium-heavy class, in part because of the relatively lengthy durability tests required for these vehicles.[9]

Transit buses operate primarily in urban environments and may be equipped with single-trap systems. In contrast to that of line-haul trucks, the operating cycle of transit buses (multiple stops and starts in urban areas) creates the worst scenario for particulate emissions. Development of feasible systems may be difficult. The transit bus engine is located in the rear of the vehicle along with several other major components. Unless the trap-oxidizer can directly replace an existing component such as the muffler, the rear of buses may have to be redesigned. Some evidence indicates that adding a trap to the exhaust system would allow the muffler to be deleted.[15]

4.7 COMPLETE SYSTEMS

It is now necessary to briefly review the synergistic effects of the complete trap-oxidizer systems before an assessment of their costs can be made. Four types of trap-oxidizer systems are now applicable to HDDVs:

- Ceramic monolith trap with bypass oil burner or electric regeneration.
- Ceramic monolith trap with self-regeneration through either a fuel additive or base-metal catalysts.
- Ceramic fiber "candle" trap with regeneration by catalyst injection.
- Catalytic wire mesh trap with regeneration by HC and CO oxidation.

Table 5 lists the salient features of each of these systems and summarizes their effectiveness, durability, performance, fuel economy, safety, environmental effects, and development status.

TABLE 5 Summary of Trap-Oxidizer Systems

System:	**Ceramic monolith trap with bypass/burner or electric regeneration**
Comments	Limitations on maximum trap size may result in multiple traps for heavy HDDTs; single-trap system may be suitable for light HDDTs and most medium HDDTs.
Effectiveness	Efficiency may exceed 90%; most effective at capturing soot; however, much of the organic fraction of the particulate goes through, including mutagenic species.
Durability and Reliability	Could be significant problems (particularly reliability), given the complex controls required for effective regeneration. Thermal-stress-related damage appears to be a significant problem.
Performance and Fuel Economy Effects	Can affect turbocharger performance; significant effect on fuel economy possible unless turbocharger is carefully matched; additional use of fuel in burner could lower fuel economy. Electric regeneration may provide marginal savings in energy use.
Safety and Environmental Effects	Serious questions about safety; diesel fuel line near exhaust system, plus regeneration, increases fire risk. Environmental impact should be minimal.

TABLE 5 (Cont'd)

Other Factors	Easily tampered with or bypassed completely by jamming bypass valve open.
Development Status	Considered leading system by Caterpillar and Cummins; cost and reliability problems have restricted development.
Overall Assessment	Unattractive from standpoints of cost and reliability; may be applicable for line-haul trucks and transit buses.

System: Ceramic monolith trap with self-regeneration through catalytic fuel additives or base-metal catalysts

Comments	See ceramic monolith trap with bypass/burner system.
Effectiveness	Same as ceramic monolith trap with bypass/burner system. However, impact of metal catalyst on trap performance must be evaluated.
Durability and Reliability	Reliability should be adequate. Durability may be a problem; accumulation of catalytic metal in the trap may require replacement or cleaning of trap, thus raising costs.
Performance and Fuel Economy Effects	Slight reduction in engine performance and slight increase in fuel use because of pressure drop through trap; fuel use is affected less because regeneration is more frequent and requires no fuel.
Safety and Environmental Effects	Major safety concern is onboard storage of organo-metallic additives, which are highly flammable and mostly toxic. Environmental impacts could arise from spillage of additive and release of catalytic metal in exhaust.
Other Factors	EPA may need to define acceptable additives.
Development Status	Development for LDVs is advanced; may be suitable for HDDTs.
Overall Assessment	Low cost, rapid development, and reliability appear to enhance probability of success for this approach in HDDTs; disadvantages are related to periodic need to free the traps of catalytic metal deposits.

TABLE 5 (Cont'd)

System: Ceramic fiber trap with regeneration by catalyst injection	
Comments	Consists of numerous "candles" of woven silica-fiber yarn on a perforated metal substrate and impregnated with an inorganic material to improve filtration. Would include back pressure sensor, temperature sensor, and control logic, plus a method to inject the catalyst powder into the exhaust stream.
Effectiveness	Trap efficiency reported to be 60-90% when clean; this increases with trap loading.
Durability and Reliability	Durability and reliability appear good. Problems include caking of powdered additive when combined with water, and retention of noncombustible metallic ash in the trap, resulting in increased back pressure with time. Cleaning or replacing trap could be expensive.
Performance and Fuel Economy Effects	Low back pressure of system reduces effect on fuel economy to approximately 1%.
Safety and Environmental Effects	Safety problems appear to be no worse than with other systems; environmental problems may relate to release of catalyst additives.
Other Factors	May be the most attractive system for HDDVs; may affect work of U.S. manufacturers because patent is held by a West German company.
Development Status	Daimler Benz has run several preliminary tests.
Overall Assessment	Single-source developer may present a problem; may become a very strong contender in the market.
System: Catalyst wire mesh trap with regeneration by HC and CO oxidation	
Comments	One or two traps each with several cylindrical wire mesh filtering elements and adequate manifolding. Likely system for most light and medium HDDVs.
Effectiveness	Less effective than ceramic monolith in capturing soot. However, removes all soluble organic particulates fractions. Increases sulfate emission at high exhaust temperatures.

TABLE 5 (Cont'd)

Durability and Reliability	Loss of catalyst's effectiveness with time is of concern; useful life may not exceed 150,000 miles; replacement expensive.
Performance and Fuel Economy Effects	Same as for ceramic monolith/self-regeneration system.
Safety and Environmental Effects	Safety concern restricted to slightly increased fire risk; environmental concern relates to sulfate emissions.
Other Factors	May be acceptable to consumer if low-sulfur fuels becomes available.
Development Status	Development is fairly advanced except for solution of sulfate emission problem.
Overall Assessment	Appears very attractive; high cost of system and sulfate emission problems may affect acceptance; most promising for light HDDVs if low-sulfur diesel fuel becomes available.

5 EPA COST ESTIMATES

5.1 FLEETWIDE COSTS OF MEETING THE PARTICULATE STANDARDS

The EPA summarized its estimates of the national economic impact of meeting the particulate standards in its March 1985 rulemaking on NO_x and particulate emissions.[12] (The impact of the NO_x regulations on the HDDV fleet was also included in the rulemaking, but is not included here.) These estimates are presented below as the starting point for a detailed analysis of EPA's cost estimates for particulate trap-oxidizers. Aggregate cost estimates are given for 1988-1990, 1991-1993, and 1994-1996 because increasingly stringent regulations go into effect in 1988, 1991 and 1994. In all cases, "cost to the manufacturers" is the total cost of R&D, recertification testing, and necessary hardware for three model years' production of HDDVs. The costs are in 1984 dollars discounted to the year of origin at 10% per year.

For 1988-1991, the discounted cost to manufacturers of the 0.6-g/bhp-hr particulate standard is estimated to be $43.9 million. This cost is expected to be recovered by the manufacturers through an increase of $46 in the purchase price of an average 1988-1990 model HDDV. No fuel economy penalty is expected and, therefore, no associated costs are anticipated.

For 1991-1994, the cost to manufacturers of the 0.25-g/bhp-hr particulate standard (with 0.10 g/bhp-hr required for transit buses) is estimated to be $403 million, discounted to 1991. These standards could result in a fleetwide first-price increase of $336 per vehicle. (This price increase represents the total cost increase for trucks equipped with trap-oxidizers averaged over the entire fleet.) Only 60% to 70% of the trucks are assumed to be equipped with trap-oxidizers, due to emissions averaging. The higher percentage will apply in the early years and thus the fleetwide first-price increase might be higher in the first year(s) of the standard. The $336 is the stabilized first-price increase for the 1991 standard, assuming that about 60% of the truck engines have trap-oxidizers.

For the 1991 standard, EPA projects a fuel economy penalty of 1% to 1.5% for trucks equipped with trap-oxidizers; transit buses will experience a 1.5% penalty. This results in an estimated fleetwide discounted lifetime cost of $227 to $330 per vehicle, with about 60% of trucks and 100% of buses assumed to have traps. The EPA estimates that fleetwide discounted lifetime maintenance cost increases due to trap-oxidizers will be $62. Both of these costs may be somewhat higher initially, but the costs shown here represent stabilized changes in operating and maintenance costs.

Combining the estimates of stabilized first-price increase, fuel costs, and maintenance costs results in an estimated fleetwide increase of $625 to $728 for the average cost of an HDDV (Table 6). The three-year (1991-1993) aggregate cost of the 1991 model year particulate standards, discounted to 1991, is estimated to be $746 million to $868 million, with the range due to the fleetwide variance in fuel economy penalties.

TABLE 6 Summary of EPA Discounted Fleetwide Cost Estimates for Particulate Control (1984 $)

Years and Standard (g/bhp-hr)	Manufacturers' Aggregate Cost (million $)	Purchase Price Increase ($/vehicle)	Fuel Economy Penalty ($/vehicle)
1988-1990:0.6	43.9	46	--
1991-1994:0.25 (0.1 bus)	403	336	227-330
1994-1996:0.1	185	163	103-154

Years and Standard (g/bhp-hr)	Increased Maintenance Cost ($/vehicle)	Total Cost Increase to Consumer ($/HDDV)
1988-1990:0.6	-	46
1991-1994:0.25 (0.1 bus)	62	625-728
1994-1996:0.1	30	296-347

Source: Ref. 8.

In 1994, the particulate standard will drop to 0.10 g/bhp-hr for all HDDVs. This will increase trap usage from 60-70% of the non-bus engines in 1991-1993 to 90% in 1994 and beyond. The three-year (1994-1996) cost of this standard to the manufacturer is expected to be $185 million, discounted to 1994. This would result in a fleetwide first-price increase of $163 per HDDV. Operating and maintenance costs to the consumer, expressed in terms of the incremental cost increases incurred by about 30% of the non-bus HDDV fleet, are estimated to be $133 to $184, spread across the entire HDDV fleet. Of these amounts, $30 is attributable to trap maintenance and $103 to $154 to the fuel economy penalty of 1% to 1.5%. As shown in Table 6, the total fleetwide increase to the consumer, discounted to 1994, is thus $296 to $347. The three-year aggregate cost to the nation of the 1994 particulate standard is therefore estimated to be $336 million to $394 million, with the range due to fleetwide variance in estimated fuel economy penalties.

The various fleetwide costs for HDDV particulate control in the three time periods are summarized in Table 6. Derivation of per-vehicle costs on both a fleetwide and individual vehicle basis will be examined in greater detail below, with the focus on 1991 costs. Particulate trap-oxidizers, the focus of this study, are not needed for HDDVs to meet the 1988 standard. The EPA's estimates of costs associated with the 1994 standard simply represent the extension of costs incurred by 60% of the HDDVs in 1991 to another 30% of those vehicles in 1994. (The EPA noted, however, that it would be reasonable to expect that engineering experience gained throughout the early 1990s will make the application of trap-oxidizers to new engine families in 1994 less difficult than in 1991, therefore lowering the 1994 cost. Further, EPA indicated that with the long lead time for the 1994 standard, a less costly trap-oxidizer system than it assumed for 1991 might be available in 1994.) The following discussion of the 1991 costs examines EPA's estimated costs to manufacturers and costs to users.

5.2 COST TO MANUFACTURERS, 1991

The EPA's estimates of the cost to manufacturers of the particulate standards are divided into fixed costs and variable costs.[8]

5.2.1 Fixed Costs

Research and development costs are separated by EPA into three categories: (1) general development, (2) specific engine family designs, and (3) electronic control development. The EPA allotted $2.8 million to each of the seven largest HDDE manufacturers to develop general trap-oxidizer systems (assuming 20 person-years of effort per manufacturer at $60 per hour); smaller manufacturers were expected to rely on guidance for engine designs from trap-oxidizer manufacturers. Designs for specific engine families were assumed to require an additional two person-years of effort and to be required by about 70% of the engine families. Average cost is projected to be about $230,000 per family. Development of electronic controls was expected to cost $115,000 per engine family. Including contingency factors, total R&D costs for particulate traps are projected to be $43 million. Emission certification testing is projected to add another $6.5 million. Thus, EPA's estimated total fixed costs to meet the 1991 HDDE standards are $49.5 million, as shown in Table 7.

TABLE 7 EPA Estimates of Total Fixed Costs for 1991 HDDE Particulate Standards (million 1984 $, undiscounted)

Year	Development Cost	Certification Cost	Total Cost
1987	8.0	-	8.0
1988	20.0	-	20.0
1989	13.0	1.0	14.0
1990	2.0	5.5	7.5
Total	43.0	6.5	49.5

Source: Ref. 8.

5.2.2 Variable Costs

The EPA evaluated the costs of three trap-oxidizer systems in its March 1985 Regulatory Impact Analysis (RIA): the ceramic monolith trap with bypass/burner, the ceramic monolith trap with electrical regeneration, and the ceramic fiber trap with catalytic regeneration as developed by Daimler Benz (EPA previously determined that the catalytic wire mesh system was quite expensive and thus did not include this system in the RIA).[8] Of the three, the most fully developed system is the ceramic monolith with bypass fuel burner. The variable cost of each system was determined by taking the manufacturers' cost of each component, as estimated by Jack Faucett Associates and Mueller Associates,[16,17] and multiplying it by a factor of 1.29 to allow for manufacturers' overhead and profit in addition to dealer costs. The Faucett and Mueller estimate of manufacturers' costs was derived from costs of analogous hardware and from extensive interaction with industrial and/or commercial sources. Where direct costs were not available, EPA estimated the costs using previous work by Rath and Strong, Inc.,[18] in combination with information from Mueller Associates and other sources.

Table 8 shows the costs of various components of the HDDE trap-oxidizer systems and Table 9 shows the total costs of the systems, as defined by EPA. The ceramic monolith trap with fuel burner regeneration is estimated to cost $370 per light HDDE, $448 per medium HDDE, and $574 per heavy HDDE. The cost of the ceramic monolith trap with electrical regeneration is similar in all three categories. The ceramic fiber trap with catalytic regeneration may be the most economical system, with estimated costs significantly below those of the other two systems.

5.2.3 Total Costs to Manufacturers

Based on these cost estimates and other forecasts, EPA estimated the total manufacturers' costs for the 1991 standards (Table 10). The R&D costs were derived as

TABLE 8 EPA Estimates of Component Costs for HDDE Trap-Oxidizer Systems (1984 $)

	Ceramic Monolith with Fuel Burner			Ceramic Monolith with Electrical Regeneration			Ceramic Fiber with Catalytic Regeneration		
Cost Category	Light HDDE	Medium HDDE	Heavy HDDE	Light HDDE	Medium HDDE	Heavy HDDE	Light HDDE	Medium HDDE	Heavy HDDE
Burner Can	21	21	21	-	-	-	-	-	-
Fuel Delivery System	14	14	14	-	-	-	-	-	-
Fuel Ignition System	35	35	35	-	-	-	-	-	-
Auxiliary Air System	64	64	64	56	56	56	-	-	-
Exhaust Diversion System	64	67	73	64	67	73	-	-	-
Electronic Control System	71	75	75	71	75	75	59	62	62
Electrical System	-	-	-	78	89	102	-	-	-
Catalyst Dispenser System	-	-	-	-	-	-	53	53	53
Catalyst	-	-	-	-	-	-	5	9	18
Catalyst System Exhaust Modifications	-	-	-	-	-	-	33	42	71
Total	269	276	282	269	287	306	150	166	204

Source: Ref. 8.

TABLE 9 EPA Estimates of Costs for HDDE Trap-Oxidizer Systems (1984 $)

HDDE Size Category	Ceramic Monolith with Fuel Burner			Ceramic Monolith with Electrical Regeneration			Ceramic Fiber with Catalytic Regeneration		
	Trap	System	Total	Trap	System	Total	Trap	System	Total
Light	101	269	370	101	269	370	73	150	223
Medium	172	276	448	172	287	459	106	166	272
Heavy	292	282	574	292	306	598	140	204	344

Source: Ref. 8.

TABLE 10 EPA Total Estimated Manufacturers' Cost for 1991 Particulate Standards (million 1984 $)

Year	R&D and Testing	Variable Cost	Undiscounted Total Cost	Discounted[a] Total Cost
1987	8.0	-	8.0	11.7
1988	20.0	-	20.0	26.6
1989	14.0	-	14.0	16.9
1990	7.5	-	7.5	8.2
1991	-	126.0	126.0	126.0
1992	-	125.5	125.5	114.1
1993	-	119.9	119.9	99.1
Total	-	-	420.9	402.6

[a]Discounted at 10% to 1991.

Source: Ref. 8.

discussed in Sec. 5.2.1. The total variable costs in the table require further explanation; they are the result of the combination of the per-vehicle variable costs discussed in Sec. 5.2.2 and estimates of vehicle sales (Fig. 4) and trap usage. Further, they assume use of only the ceramic monolith trap with fuel burner because of the greater uncertainty associated with the other two systems.

Determination of per-average vehicle variable cost used by EPA can be formulated as follows:

$$FVC = ab + cde$$

where:

FVC = fleetwide variable cost per vehicle in a specific year,

a = bus sale percentage of total HDDV sales,

b = variable cost of bus,

c = truck sale percentage of total HDDV sales,

d = variable cost of truck, and

e = percentage of trucks equipped with system.

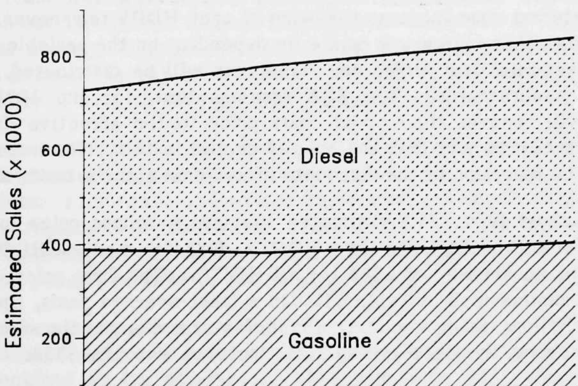


FIGURE 4 Estimated Sales of Heavy-Duty Vehicles (Based on information in Ref. 19)

Transit bus sales are volatile from year to year but are not expected to account for more than 2% of total HDDV sales. Total variable costs for the trap-equipped transit bus, the engine of which is classified as a medium HDDE because of its horsepower rating, are simply that for all medium HDDEs, or $448 (from Sec. 5.2.2). Truck sales account for 98% of total HDDV sales. The average variable cost for HDDTs with trap-oxidizers is found by sales-weighting the system cost for each size category. The EPA estimated that HDDT sales are distributed as 36% light, 27% medium, and 37% heavy. Sales-weighting of the various system costs stated in Sec. 5.2.2 with this distribution provides an average truck cost of $467.

The EPA further assumed that the percentage of trucks using traps would be 70% in 1991 and 60% in 1993 (and EPA apparently interpolated these values for the intervening year).

Based on the above equation, the fleetwide average variable cost per vehicle was estimated by EPA to be $329 in the short term (1991) and $284 in the long term (1993). The total variable costs shown in Table 10 are then simply the product of these average per-vehicle costs times the total diesel sales estimated for 1991-1993. These costs then were combined with fixed costs to determine total costs to manufacturers.

5.3 COST TO USERS, 1991

5.3.1 First Costs

Manufacturers must increase the price of each HDDV to recover their fixed costs and variable costs. This increase is primarily dependent on the variable cost per vehicle, the number of vehicles over which the fixed cost will be distributed, and the cost of capital to the manufacturer. The EPA assumes that, for the 1991 standards, the manufacturers will recover their fixed costs prior to the effective date of the more stringent 1994 standards, and that the cost of capital is 10%. The increase in first cost would therefore be a portion of the discounted fixed cost and the hardware cost.

For the short term, EPA estimated that the purchase price increase for trap-equipped trucks would be $457 for light HDDTs, $535 for medium HDDTs, and $661 for heavy HDDTs, for an average of $553 for all HDDTs. The first price of a bus is $535. These costs are summarized in Table 11. On a fleet-average basis, the costs would be about $390. In the long term, assuming a manufacturer charges the same per vehicle for its fixed cost recovery, the fleet-average cost increase would be $336.

5.3.2 Fuel Economy

The EPA assumed a fuel economy penalty of 1% to 5% for trucks and 1.5% for buses, based on trap volumes estimated by EPA. For HDDTs, the discounted lifetime costs of a 1% penalty for each size category were shown to be $54 for light HDDTs, $259 for medium HDDTs, and $705 for heavy HDDTs. These estimates are based on a fuel cost of $1.20/gallon and lifetime mileages of 110,000 in 10 years for light HDDTs;

TABLE 11 EPA Estimates of Total Costs to User for Particulate Trap-Oxidizer Systems[a] (1984 $)

Truck/Bus Size Category	Purchase Price Increase	Increased Energy Costs	Maintenance Costs	Total Costs
Light HDDT	457	54-81	66	577-604
Medium HDDT	535	259-389	107	901-1030
Heavy HDDT	661	705-1058	133	1499-1852
Bus	535	1070	107	1712

[a]Assumes use of ceramic monolith trap with bypass/burner regeneration.

Source: Ref. 8.

270,000 in nine years for medium HDDTs, and 520,000 in eight years for heavy HDDTs. Based on limited tests at GM with small engines, EPA estimates a 1% penalty in fuel economy due to back pressure. A 0.5% penalty for regeneration was also estimated by EPA, assuming an estimated burn time of five minutes every 100 to 175 miles. Based on these figures, the average discounted lifetime cost of the fuel penalty for the various truck categories is shown in Table 11. Sales-weighting of the trucks would result in an average cost penalty of $350 to $525 per trap-equipped truck.

An average annual transit bus mileage of 45,000 miles and an average life of 12 years is assumed. Diesel fuel for buses is estimated to be less expensive than that for non-bus applications: $1.00/gallon. Based on these assumptions, the estimated 1.5% fuel economy penalty results in a discounted lifetime fuel cost of $1070 for each bus. Fleetwide (i.e., including trucks without traps), the average HDDV will incur a short-term fuel economy penalty of $261 to $381 and a long-term penalty of $227 to $330.

These fuel-economy penalties assumed the use of a monolith trap with fuel-burning regeneration; for electric regeneration, the penalty would be comparable because of the energy required by the alternator. However, with the ceramic fiber trap, the penalty would be less by approximately 0.5%, ranging from 0.5% to 1.0%.

5.3.3 Maintenance

In the regeneration system, the engine-temperature and trap-temperature sensors will require periodic replacement. Use of one trap in all vehicle types and one sensor replacement per light HDDT, two per medium HDDT, and three per heavy HDDT was assumed by the EPA. The discounted costs for the three classes of vehicles are estimated to be $35 for light HDDT, $57 for medium HDDT, and $71 for heavy HDDT and include labor and sensor costs. The EPA estimates that trap maintenance will parallel sensor maintenance and will cost about $50 per event. Discounted at 10% to the year of purchase, the costs are $31 for light HDDT, $50 for medium HDDT, and $62 for heavy HDDT. Total maintenance costs for the different truck and bus categories are shown in Table 11. The average for all trucks with traps is thus $102, and the total cost for a transit bus is $107. On a fleetwide basis, the cost per HDDV is $72 in the short term, declining to $62 in the long term.

5.3.4 Total User Cost

The total cost to the purchaser includes the first-price increase and the lifetime discounted costs for fuel economy and maintenance. The cost for each trap-equipped light HDDT is $577 to $604; for a medium HDDT, $901 to $1030; and for a heavy HDDT, $1499-1852 (see Table 11). For an average HDDT with a trap, the total cost is $1050 to $1180. For a bus, it is $1712. Over the entire fleet, the average cost is $723 to $843 in the short term, declining to $625 to $728 in the long term. The long-term figures are summarized in Table 6.

6 MANUFACTURER COST ESTIMATES

Manufacturer estimates of the costs of particulate trap-oxidizer systems are shown in Table 12.[4,8,13] Certain details of these estimates are unclear. In the public docket, these costs were referred to as "total system costs," "cost to consumer," or "consumer effects," and no breakdown of component costs was available in most cases (Cummins provided a partial breakdown of its cost estimates, as shown in the table).[8,13] These costs may include some of the fixed and operating costs or may reflect the full retail price of a replacement unit rather than the incremental cost of a unit in a new vehicle. Thus the information provided by the trap manufacturers is too vague to be analyzed with any degree of certainty.

TABLE 12 Manufacturer Cost Estimates for Trap-Oxidizer Systems

Manufacturer	Cost ($)	Description
International Harvester	1285-2070	Medium HDDE, single trap
	4710	Medium HDDE, single trap
	7210	Medium HDDE, dual trap if required
Ford	2200	No comment
Cummins	2810-3270	Heavy HDDE, possible dual-trap option
Trap Substrate Material	720-1080[a]	
Trap Casing and Ceramic Mounting	250	
Diesel Burner for Regeneration	400	
Electric Air Blower for Burner	175	
Miscellaneous Control Costs	650	
GM	575-900	Light HDDE
	2300	Medium HDDE, single trap
	4000	Medium HDDE, dual trap
Saab	2500+	No comment
Caterpillar	2000-	No comment

[a]Based on trap volume of 60 to 90 L, which according to EPA may greatly exceed actual requirements.

Source: Refs. 4, 8, 13.

As seen from the table, manufacturer estimates vary from a low of \$575 to \$900 to as much as \$7210. At present, with little or no knowledge of the exact trap-oxidizer systems to be used for specific applications, it is not surprising that the manufacturer estimates are consistently high. It appears that the manufacturers are simply applying all possible caveats to arrive at values that could only be construed as upper limits.

Of the manufacturers providing comments to Public Docket A-80-18, only a few provided estimates of the fuel economy impact of particulate traps alone (as opposed to the fuel economy impact of combined NO_x and particulate regulation). In 1982, Caterpillar and GM provided estimates of 1% and 1% to 2% impact, respectively.[4,5] More recently, Cummins projected a fuel economy impact of 2.6%; of this, 1.6% was due to back pressure increase and 1% was due to the burner.[8] Cummins further estimated that this would increase to 4.2% if trap volume was reduced to 30 L.

7 COST ESTIMATES BY ENERGY AND RESOURCE CONSULTANTS, INC.

A recent assessment of a variety of trap-oxidizer systems, their specific features and application potential for various diesel engine types, and their costs was published by Energy and Resource Consultants, Inc. (ERC), a subcontractor to EPA.[9] Combining engineering judgment with a review of data that includes confidential information from manufacturers, and working within the constraints of the EPA framework, ERC estimated costs of four systems: the ceramic monolith trap with bypass/burner regenerator system, the ceramic monolith trap with self-regeneration, the catalyzed wire mesh trap with regeneration by HC and CO oxidation, and the ceramic fiber trap with regeneration by catalyst injection. The merits and drawbacks of each of these systems were summarized in Table 5. In this section, ERC's derivation of costs for the ceramic monolith trap with bypass/burner regeneration and the ceramic fiber trap with regeneration by catalyst injection will be discussed. The ERC estimates for the other two systems are not presented here because EPA did not estimate their costs in its 1985 RIA.

The ERC report estimates the increases in purchase price and operating and maintenance costs for each of the four major classes of HDDVs using a trap-oxidizer system. The increase in purchase price is termed the Retail Price Equivalent (RPE) and is derived from earlier analyses by Putnam, Hayes and Bartlett, Inc.,[20] and Rath and Strong, Inc.[18] These analyses were designed for, and based on data for, LDVs. Thus, some modifications by ERC were required to adapt them tentatively to HDDVs.

The ERC equation for the RPE defines the increase in selling price as a result of incorporating a trap-oxidizer system manufactured by an outside organization:

$$RPE = [(SP + AL + AO)MM + RD + TE]DM$$

where:

SP = price charged by supplier to the manufacturer,

AL = direct cost of assembly labor for mounting the device in the vehicle,

AO = manufacturer assembly overhead cost per unit,

MM = manufacturer markup percentage,

RD = manufacturer R&D cost per unit,

TE = manufacturer tooling cost per unit, and

DM = dealer markup percentage.

7.1 CERAMIC MONOLITH TRAP WITH BYPASS/BURNER REGENERATION

Table 13 shows costs to the manufacturer and the initial and lifetime cost to the user of the ceramic monolith trap with bypass/burner regeneration. The supplier price estimated for each of the major components of the trap-oxidizer system is reported to be based on data from manufacturers, on prices of similar products currently in use, and on engineering judgment and is the projected mass-production price. Labor required to assemble and install a trap-oxidizer system was estimated by ERC on the basis of engineering judgment and the apparent difficulty of mounting the unit. Assembly labor costs were estimated at $20/hour and the assembly overhead for HDDVs was assumed to be the same 40% as estimated by Putnam, Hayes and Bartlett for LDVs.

The R&D and tooling costs are reported to be primarily guesswork. No one has a fully developed trap-oxidizer system at present, and the actual costs of development are not precisely defined. In contrast to EPA's estimate of $19.6 million ($2.8 x 7) for the seven manufacturers for general development R&D, $238,000 for engine-specific designs for each of 88 engines families, and $115,000 per engine family for development of electronic controls, GM claims to have spent more than $64 million on trap-oxidizer development. General Motors must still cover the most expensive facets of development, that is, fleet testing, adaptation to manufacturing, durability assurance, and certification testing. The ERC estimate for the total R&D cost per manufacturer for this bypass/burner system is $30 million for the medium-heavy and heavy-heavy classes. Tooling expenses were estimated by ERC at $10 million.

It was assumed by ERC that the typical heavy-duty manufacturer produces 40,000 units per year and that the tooling and R&D costs are recovered at 20% per year; this gives an R&D cost per unit of $150, with a further $50 for tooling costs. These costs were doubled by ERC for transit buses, reflecting the very small bus production volume (about 2500 units per year, in total). For light-HDDVs, ERC reduced the costs by a factor of 10, reflecting the much larger volume and the relative ease of adapting light-duty trap-oxidizer technology to the light-heavy class.

The manufacturer markup term used by ERC accounts for both corporate overhead and profits. In a study conducted for EPA and using financial data from 1979 through 1983, this factor was estimated to be 1.11 (11% markup) for LDV manufacturers.[20] In the case of heavy-duty manufacturers, however, there are often not one but two corporate markups to consider -- that of the engine maker and that of the vehicle assembler (light-duty manufacturers generally fill both roles). The duplication of corporate staffs should result in a higher markup, as should the smaller size and lower volume (and thus lower economies of scale) of heavy-duty manufacturers. In addition, the years 1979-1983 are generally regarded as disastrously unprofitable for both light- and heavy-duty manufacturers. Thus, profit margins estimated from data in these years would be expected to be too low. Taking all of these factors into account, ERC assumed that a markup factor of 20% is probably more representative than the value of 11%. The higher value is used in Table 13.

The dealer markup term was previously estimated in a study for EPA as 1.05 for passenger cars and 1.06 for trucks.[20] Again, this value was based on data for 1979-1983 and is thus probably too low to represent the long-term average. There are also major

TABLE 13 ERC Cost Estimates (and Related Data) for Ceramic Monolith Trap with Bypass/Burner Regeneration (all costs in 1984 $)

Cost Category	Light-Heavy (8,500-14,000 lb GVW)	Medium-Heavy (14,001-50,000 lb GVW)	Line Haul (>50,000 lb GVW)	Transit Bus
Initial Cost to Manufacturer				
Trap	72.00	120.00	240.00	150.00
Container and Piping	50.00	60.00	120.00	60.00
Regeneration and Control System	170.00	180.00	220.00	180.00
Modifications to Vehicle	20.00	40.00	80.00	100.00
Total Component Cost	312.00	400.00	660.00	490.00
Assembly Labor (hr)	2.00	3.00	5.00	4.00
Cost @ $20/hr	40.00	60.00	100.00	80.00
Assembly Overhead @ 40%	16.00	24.00	40.00	32.00
Total Cost to Manufacturer	368.00	484.00	800.00	602.00
Manufacturer Markup @ 20%	73.60	96.80	160.00	120.40
Estimated Tooling Cost per Unit	5.00	50.00	50.00	100.00
Estimated R&D Cost per Unit	15.00	150.00	150.00	300.00
Increase in Dealer Cost	461.60	780.80	1160.00	1122.40
Dealer Markup @ 8%	36.93	62.46	92.80	89.79
Initial Cost to Consumer	498.53	843.26	1252.80	1212.19
Operating Costs				
Vehicle Lifetime (mi)	120,000	250,000	500,000	250,000
Vehicle Lifetime (yr)	8	8	8	8
Maintenance Costs				
Per 100,000 Miles	70.00	70.00	100.00	70.00
Discounted Lifetime Cost	56.02	116.70	333.43	116.70
Fuel Consumption				
Base Fuel Economy (mpg)	16.20	8.81	6.44	6.00
Reduction Due to Trap (%)	2.5	2.5	2.0	3.9
Cost of Fuel ($/gal)	1.30	1.30	1.30	1.30
Discounted Lifetime Cost	160.54	615.02	1346.16	1083.66
Trap Replacement Cost				
Trap Lifetime (mi)	150,000	250,000	250,000	150,000
Trap Replacements Needed	0	0	1	1
Cost of Replacement	300.00	416.00	776.00	476.00
Discounted Replacement Cost	0.00	0.00	530.02	295.56
Total Operating Costs	216.56	731.72	2209.61	1495.92
Total Life-Cycle Costs	715.09	1574.98	3462.41	2708.11

Source: Ref. 9.

differences between sales of LDVs and heavy-duty trucks -- generally, a truck dealer's technical expertise must be much greater and the dealer's operating costs are probably also higher. For this reason, ERC regards a dealer markup of 8% more appropriate than the 6% estimated for LDVs.

Inserting the values into the equation and performing the calculations results in the estimated increased cost to the purchaser shown in Table 13. However, ERC warns that, considering the uncertainties inherent in estimating the cost for a system that has not even been designed yet, these values should be taken as only very rough and approximate. Moreover, ERC considers the costs to be somewhat conservative (that is, the actual costs may be higher). One area where costs may have been underestimated is in allowing for warranty and recall. This allowance is supposed to be included in the manufacturer markup, but the serious reliability questions surrounding trap-oxidizers in general, and especially the bypass/burner, make it questionable whether the manufacturer markup is adequate.

In addition to the initial purchase price increase of the trap-oxidizer, the system will also entail significant operating and maintenance expenses. These expenses and the assumptions used by ERC are shown in Table 13. The vehicle lifetimes and lifetime mileages are considered to be reasonably representative of vehicles in each class, although of course individual vehicles would vary. Maintenance cost per 100,000 miles was estimated by ERC through engineering judgment and consideration of the system's mechanical complexity. This cost was the spread over the life of the truck and discounted to the year of purchase at a 10% (real) rate.

Base fuel-economy values assumed for each class of truck (shown in Table 13) are those estimated for 1992 by Energy and Environmental Analysis, except for transit buses, for which the estimate was made by the authors of the ERC report.[21] These represent substantial improvements over present-day values and probably could not be achieved in the face of a 4.0-g/bhp-hr NO_x standard. The effect of relaxation to a 5.0-g/bhp-hr NO_x standard is unclear. Increased fuel consumption due to the trap-oxidizer was estimated by ERC and may be somewhat optimistic. The magnitude of this fuel economy penalty could be altered by how well the turbocharger characteristics are matched to the trap-oxidizer system/engine combination. According to ERC, the lowest possible penalty is about 2.0% to 2.5%, considering that the burner regeneration process also consumes fuel, while a penalty of 3% to 4% would not be at all surprising. The penalty for buses is estimated by ERC to be somewhat greater, due to the constraints of trap placement in buses. Calculating the discounted lifetime fuel cost of the system by dividing the average miles per year by the fuel economy rating, ERC then multiplied by the fuel-economy penalty to arrive at the average cost per year. This was then discounted (at 10%) to the year of purchase to give the discounted lifetime fuel cost.

The trap replacement frequencies shown in Table 13 were estimated by ERC with what they consider to be optimistic estimates of trap plugging rates and average lifetimes. As the table indicates, only line-haul trucks and transit buses are expected to require trap replacement. Replacement cost was estimated as parts and labor, with the parts cost taken as the supplier's price for the trap marked up 100% to reflect the premium charged in the aftermarket. The labor cost of the trap replacement was estimated at two labor hours, at a cost of $28 per hour, and the total was discounted to the year of purchase at 10% per year.

As Table 13 indicates, trap-oxidizers would be fairly expensive, especially in heavy-duty vehicles. The reader is cautioned, however, that these are crude estimates based on a technology still under development. Accordingly, they should be treated with appropriate caution. In performing these estimates, ERC has claimed a tendency to err on the side of optimism -- thus they project that the actual costs would probably not be less than those shown, but might well be significantly more if unforeseen problems occur during development.

7.2 CERAMIC FIBER TRAP WITH REGENERATION BY CATALYST INJECTION

Table 14 shows ERC's cost estimates for a ceramic fiber trap with regeneration by catalytic injection. The general estimation method was described in Sec. 7.1 and is therefore not discussed here. Total life-cycle costs are quite similar to those of the ceramic monolith trap with burner, but these similarities hide important differences. Maintenance costs and fuel consumption penalties may be lower with the ceramic fiber trap, but the need for trap replacement may be higher.

TABLE 14 ERC Cost Estimates (and Related Data) for Ceramic Fiber Trap with Catalytic Regeneration (all costs in 1984 $)

Cost Category	Light-Heavy (8,500-14,000 lb GVW)	Medium-Heavy (14,001-50,000 lb GVW)	Line Haul (>50,000 lb GVW)	Transit Bus
Initial Cost to Manufacturer				
Trap	80.00	130.00	260.00	170.00
Container and Piping	50.00	60.00	120.00	60.00
Regeneration and Control System	140.00	160.00	200.00	160.00
Modifications to Vehicle	20.00	40.00	80.00	100.00
Total Component Cost	290.00	390.00	660.00	490.00
Assembly Labor (hr)	2.00	3.00	5.00	4.00
Cost @ $20/hr	40.00	60.00	100.00	80.00
Assembly Overhead @ 40%	16.00	24.00	40.00	32.00
Total Cost to Manufacturer	346.00	474.00	800.00	602.00
Manufacturer Markup @ 20%	69.20	94.80	160.00	120.40
Estimated Tooling Cost per Unit	5.00	50.00	50.00	100.00
Estimated R&D Cost per Unit	15.00	150.00	150.00	300.00
Increase in Dealer Cost	435.20	768.80	1160.00	1122.40
Dealer Markup @ 8%	34.82	61.50	92.80	89.79
Initial Cost to Consumer	470.02	830.30	1252.80	1212.19
Operating Costs				
Vehicle Lifetime (mi)	120,000	250,000	500,000	250,000
Vehicle Lifetime (yr)	8	8	8	8
Maintenance Costs				
Per 100,000 Miles	40.00	40.00	50.00	40.00
Discounted Lifetime Cost	32.01	66.69	166.72	66.69
Fuel Consumption				
Base Fuel Economy (mpg)	16.20	8.81	6.44	6.00
Reduction Due to Trap (%)	1.0	1.0	0.75	1.25
Cost of Fuel ($/gal)	1.30	1.30	1.30	1.30
Discounted Lifetime Cost	64.22	246.01	504.81	451.52
Trap Replacement Cost				
Trap Lifetime (mi)	120,000	150,000	150,000	100,000
Trap Replacements Needed	0	1	3	2
Cost of Replacement	316.00	436.00	816.00	516.00
Discount Replacement Cost	0.00	297.79	1692.32	678.94
Total Operating Costs	96.23	610.49	2363.85	1197.15
Total Life-Cycle Costs	566.24	1440.79	3616.65	2409.35

Source: Ref. 9.

8 ANALYSIS OF THE VARIOUS COST ESTIMATES

This section compares and contrasts the EPA and ERC cost estimates for the ceramic monolith trap with bypass/burner and the ceramic fiber trap with catalyst injection. These are the only two systems for which estimates were made by both EPA and ERC. As discussed in Sec. 6, the cost information provided by the manufacturers is both scant and vague and thus is not usable for detailed cost comparisons.

Direct comparison of the EPA and ERC cost estimates cannot be made readily. While ERC used a lifetime of eight years for all vehicles, EPA used 10 years for light-heavy trucks, nine years for medium-heavy trucks, eight years for heavy-heavy trucks, and 12 years for transit buses. The EPA assumed lifetime mileages of 110,000, 270,000, 520,000, and 540,000 for light, medium, and heavy HDDTs and for buses, respectively. On the other hand, ERC assumed vehicle lifetime mileages of 120,000 (light-heavy), 250,000 (medium-heavy), 500,000 (line-haul), and 250,000 (bus).

Another difference in the two cost estimates is related to vehicle classifications. As indicated in Sec. 2, EPA classifies vehicles in Classes 2B through 5 (8500 to 19,500 lb GVW) as light-heavy; Class 6 as medium-heavy (19,501 to 26,000 lb GVW), and Classes 7 and 8 as heavy-heavy (26,001+ lb GVW). Buses were treated as medium-heavy vehicles. In contrast, ERC grouped vehicles in the 8501 to 14,000 lb range as light-heavy. Vehicles over 14,000 lb were rated as medium-heavy except for line-haul trucks above 50,000 lb. Transit buses were treated as a separate class. The overlap of ERC and EPA truck size classifications is shown in Table 15. Also, in distributing R&D and tooling costs, ERC assumed nominal distribution of vehicles for the medium-heavy and line-haul vehicles; costs for the light-heavy vehicles were reduced by a factor of 10 because of their large volume, while costs for buses were doubled because of their lower numbers.

To facilitate comparisons, the ERC costs presented previously have been recalculated assuming the same mileages and lifetimes of the EPA vehicles. Further, while the base fuel economy and fuel economy penalties assumed by ERC are used in the recalculated ERC estimates, EPA's diesel fuel cost has been assumed: $1.20 per gallon of diesel fuel for the three major classes of vehicles and $1.00 per gallon for transit buses. Tables 16-19 show the adjusted ERC costs for the four classes of vehicles and two types of trap-oxidizer systems; EPA's cost estimates are also shown. These latter estimates are essentially the same as those in Sec. 5 except for the costs for general maintenance, trap maintenance, fuel, and catalyst replacement. The discounted costs for general maintenance, trap maintenance, and fuel shown Sec. 5 were taken directly from Ref. 5 but seem to be in error, particularly for the medium- and heavy-heavy trucks and for transit buses. They have been recalculated here for all four vehicle categories, assuming an annual 10% discount rate to the year of vehicle purchase.

The discounted catalyst replacement costs derived by EPA used a factor of 4.5 to increase the initial wholesale cost of the catalyst to an assumed retail value and included a cost for the catalyst container. In this analysis, the wholesale cost is assumed and container costs are not included because the types of containers that might be used are quite variable. In general, however, the cost should be low. Finally, because of the

TABLE 15 Comparison of EPA and ERC Truck Size Categories

Manu-facturer's Weight Class	Gross Vehicle Weight (lb)	Total New Truck Sales, 1983[a]	Categories ERC	Categories EPA
2B	8,501-10,000	72,000[b]	LH	
3	10,001-14,000	22,000		LH
4	14,001-16,000	360		
5	16,001-19,500	923		
6	19,501-26,000	46,000	MH	MH
7	26,001-33,000	49,000		
8A	33,001-50,000	8,000[c]		HH
8B	≥50,001	72,000[c]	HH	

[a]Source is Ref. 22.

[b]Estimated from data in Ref. 22; assumes 6% of total sales in Class 2 is Class 2B.

[c]Estimated from data in Ref. 22, assumes 90% of total sales in Class 8 is Class 8B and 10% is Class 8A.

overlap in vehicle classifications, Table 20 provides an additional summary of the adjusted EPA and ERC costs for the various vehicle classes. Only the costs for the ceramic monolith trap with bypass/burner are given in this table.

In spite of the steps taken in this analysis to make the basis of the ERC cost estimates more comparable to those of EPA, the adjusted EPA costs are still generally lower than those of ERC, particularly for line-haul trucks and transit buses. The reasons for these differences are summarized below.

1. *The total manufacturer costs estimated by ERC for trap-oxidizer systems for each class of vehicles are usually higher than those of EPA. There are differences in the estimated costs for components, vehicle modification, and assembly.*

a. The EPA apparently includes no costs for assembly of the trap systems into the vehicles, while ERC does.

b. EPA assumes that costs arising from vehicle modification would have only a minor effect on the total cost and that provisions for averaging in the regulations may allow manufacturers to chose vehicles that need only minimum changes to meet the standard. Thus, EPA includes no vehicle modification costs. Alternatively, ERC includes vehicle modification costs. The justification is based on several sources. For example, referring to tractor-trailer combinations, International Harvester indicated concern that if two traps were mounted behind the cab, the necessary modifications to the truck body could affect several body builders. General Motors, on the other hand, indicated that while adequate room for trap/muffler combinations may be available within most medium HDDTs, traps mounted behind the cabs of heavy HDDTs may adversely affect the turning radius of the vehicle, which in turn may alter tractor-trailer offerings. Further, GM indicated that modification of buses might result in a 10% to 15% reduction in seating capacity. Finally, Cummins also indicated the general need for vehicle modifications.[13]

c. The EPA's allowance for R&D (which in turn is reflected in component costs) is approximately $5 million per manufacturer. In contrast, ERC allows $30 million per manufacturer. In view of GM's R&D costs (estimated at $40 million by EPA and $64 million by ERC for both light- and heavy-duty vehicles) and considering that their development has not reached significant levels of testing for reliability or implementation into vehicle design, the $30 million figure appears more reasonable. The numbers from ERC may even be on the optimistic side, if unforeseen problems arise during development.

2. *The EPA's allowance of 11% under the manufacturer markup is lower than ERC's at 20%.* The limited EPA allowance may not be adequate to cover warranty, recalls, marketing, and other factors. Even ERC's allowance may be conservative because the reliability of trap-oxidizer systems is unknown and because the products are still under development.

3. *The EPA's allowance for maintenance is restricted to limited action on sensor replacement and trap maintenance; no trap replacement is indicated.* However, traps may not have the lifetime that EPA projects. Estimates by ERC incorporate trap replacement. Assuming ERC's estimated trap life for the ceramic monolith trap and EPA lifetime vehicle-miles of travel, one trap

TABLE 16 Adjusted EPA/ERC Cost Estimates (and Related Data) for Light Heavy-Duty Vehicles Using Ceramic Monolith Trap with Bypass/Burner Regeneration or Ceramic Fiber Trap with Catalytic Regeneration (all costs in 1984 $)

Cost Category	Ceramic Monolith with Bypass/Burner		Ceramic Fiber with Catalyst Injection	
	EPA	ERC	EPA	ERC
Vehicle GVW (lb)	8,500-19,500	8,500-14,000	8,500-19,500	8,500-14,000
Initial Cost to Manufacturer				
Trap	69.00	72.00	73.00	80.00
Container and Piping	32.00	50.00	--	50.00
Regeneration and Control System[a]	269.00	170.00	150.00	140.00
Modifications to Vehicle[b]	--	20.00	--	20.00
Total Component Cost	370.00	312.00	223.00	290.00
Assembly Labor @ $20/hr[c]	--	40.00	--	40.00
Assembly Overhead @ 40%[c]	--	16.00	--	16.00
Total Cost to Manufacturer	370.00	368.00	223.00	346.00
Manufacturer Markup @ 20%[d,e]	--	73.60	--	69.20
Estimated Tooling Costs/Unit[d]	--	5.00	--	5.00
Estimated R&D Costs/Unit[d]	87.00	15.00	87.00[f]	15.00
Increase in Dealer Costs	457.00	461.60	310.00	435.20
Dealer Markup at 8%[d,g]	--	36.93	--	34.82
User First Cost	457.00	498.53	310.00	470.02
Operating Data and Costs				
Vehicle Lifetime (mi)	110,000	110,000	110,000	110,000
Vehicle Lifetime (yr)	10	10	10	10
Maintenance Costs				
Per 100,000 Miles	--	70.00	--	40.00
Discounted Lifetime Cost	35.02[h]	97.30	35.02[h]	27.04
Discounted Trap Maintenance Costs	31.70[i]	--	31.70[i]	--
Total Cost	66.72	97.30	66.72	27.04
Fuel Consumption				
Basic Fuel Economy (mpg)	15.50	16.20	15.50	16.20
Reduction Due to Trap (%)	1-1.5	2.5	0.5-1.0	1.0
Cost of Fuel ($/gal)	1.20	1.20	1.20	1.20
Discounted Lifetime Fuel Costs	52.55-79.28[j]	128.38	26.43-52.85	50.58
Trap Replacement Costs[k]				
Trap Lifetime (mi)	--	150,000	--	120,000
Trap Replacements Needed	--	0	--	0
Trap Replacement Costs	--	300.00	--	316.00
Discounted Trap Replacement Costs	--	0	--	0

TABLE 16 (Cont'd)

Cost Category	Ceramic Monolith with Bypass/Burner EPA	Ceramic Monolith with Bypass/Burner ERC	Ceramic Fiber with Catalyst Injection EPA	Ceramic Fiber with Catalyst Injection ERC
Discounted Catalyst Replacement Costs @ 0.16 g/gal of Fuel Using 1% Fuel Economy Penalty	--	--	2.217[l]	--
Discounted Exhaust Pipe Credit[m]	--	--	(41.00)	--
Total Operating Costs	119.57-146.00	225.68	54.42-80.85	77.62
Total Lifetime Costs[n]	576.57-603.00	724.21	364.42-390.85	547.63

[a]EPA assumes periodic sparking in the fuel ignition system, resulting in unit cost savings of \$7.00. EPA regeneration system costs include burner can, fuel delivery system, fuel ignition system, auxiliary air system, exhaust diversion system, and electronic control system. The individual costs of these items are shown in Table 8. For catalytic regeneration, catalyst dispensers and exhaust modifications replace some of these components.

[b]EPA assumes that vehicle modifications may be eliminated by using the 70% compliance clause; if a vehicle needs modification, EPA recommends that it be classified in the exempt 30% group.

[c]EPA does not include costs for assembly labor or overhead.

[d]EPA's manufacturer markup at 11%, tooling costs, estimated R&D costs/unit, and dealer markup at 6% are all included in the \$87 estimate.

[e]Manufacturer markup of 20% was used by ERC.

[f]EPA did not provide specific estimate for ceramic fiber trap system; therefore, cost assumed to be the same as for ceramic monolith trap system.

[g]Dealer markup of 8% was used by ERC.

[h]Value reported by EPA in Ref. 8 is \$35. Value used here is based on EPA estimates of one replacement of two sensors at \$29 for parts and \$28 for labor.[8]

[i]Value reported by EPA in Ref. 8 is \$31. Value used here is based on EPA estimates of one maintenance event at \$50.

[j]Values reported by EPA in Ref. 7 are \$54 to \$81.

[k]EPA does not consider trap replacement necessary.

[l]Value reported by EPA in Ref. 8 is \$19 (initial plus replacement cost). Value used here is based on a cost of \$1.46/lb catalyst. No labor costs for replacement or additions are included.

[m]Discounted exhaust pipe credit used as provided by EPA.[8]

[n]Manufacturer trap costs, which are not really lifetime costs, range from \$575 to \$900.

TABLE 17 Adjusted EPA/ERC Cost Estimates (and Related Data) for Medium Heavy-Duty Vehicles Using Ceramic Monolith Trap with Bypass/Burner Regeneration or Ceramic Fiber Trap with Catalytic Regeneration (all costs in 1984 $)

	Ceramic Monolith with Bypass/Burner		Ceramic Fiber with Catalyst Injection	
Cost Category	EPA	ERC	EPA	ERC
Vehicle GVW (lb)	19,501-26,000	14,000	19,501-26,000	14,000
Initial Cost to Manufacturer				
Trap	132.00	120.00	106.00	130.00
Container and Piping	40.00	60.00	--	60.00
Regeneration and Control System[a]	276.00	180.00	166.00	160.00
Modifications to Vehicle[b]	--	40.00	--	40.00
Total Component Cost	448.00	400.00	272.00	390.00
Assembly Labor @ $20/hr[c]	--	60.00	--	40.00
Assembly overhead @ 40%[c]	--	24.00	--	16.00
Total Cost to Manufacturer	448.00	484.00	272.00	474.00
Manufacturer Markup [d,e]	--	96.80	--	94.80
Estimated Tooling Costs/Unit[d]	--	50.00	--	50.00
Estimated R&D Costs/Unit[d]	87.00	150.00	87.00[f]	150.00
Increase in Dealer Costs	535.00	780.80	535.00	768.80
Dealer Markup [d,g]	--	62.46	--	61.50
User First Cost	535.00	843.26	359.00	830.30
Operating Data and Costs				
Vehicle Lifetime (mi)	270,000	270,000	270,000	270,000
Vehicle Lifetime (yr)	h	h	h	h
Maintenance Costs				
Per 100,000 miles	--	70	--	40.00
Discounted Lifetime Cost	72.95[i]	120.94	72.95[i]	69.11
Discounted Trap Maintenance Cost	63.99[j]	--	63.99[j]	--
Total Cost	136.94	120.94	136.94	69.11
Fuel Consumption				
Basic Fuel Economy (mpg)	8.4	8.81	8.4	8.81
Reduction Due to Trap (%)	1.0-1.5	2.5	0.5-1.0	1.0
Cost of Fuel ($/gal)	1.20	1.20	1.20	1.20
Discounted Lifetime Fuel Costs	249.31-373.96[h]	603.41	124.66-249.31	237.70
Trap Replacement Costs[k]				
Trap Lifetime (mi)	--	250,000	--	150,000
Trap Replacements Needed	--	0	--	1
Trap Replacement Costs	--	416	--	436.00
Discounted Trap Replacement Costs	--	0	--	270.72[l]

TABLE 17 (Cont'd)

Cost Category	Ceramic Monolith with Bypass/Burner EPA	Ceramic Monolith with Bypass/Burner ERC	Ceramic Fiber with Catalyst Injection EPA	Ceramic Fiber with Catalyst Injection ERC
Discounted Catalyst Replacement Costs @ 0.16 g/gal of Fuel Using 1% Penalty	--	--	10.70[m]	--
Discounted Exhaust Pipe Credit[n]	--	--	(51.00)	--
Total Operating Costs	386.25-510.9	724.35	221.30-245.96	577.53
Total Lifetime Costs[o]	921.25-1045.9	1567.61	580.3-904.96	1407.83

[a]EPA assumes periodic sparking in the fuel ignition system, resulting in unit cost savings of $7.00. EPA regeneration system costs include burner can, fuel delivery system, fuel ignition system, auxiliary air system, exhaust diversion system, and electronic control system. The individual costs of these items are shown in Table 8. For catalytic regeneration, catalyst dispensers and exhaust notifications replace some of these components.

[b]EPA assumes that vehicle modifications may be eliminated by using the 70% compliance clause; if a vehicle needs modification, EPA recommends that it be classified in the exempt 30% group.

[c]EPA does not include costs for assembly labor or overhead.

[d]EPA's manufacturer markup at 11%, tooling costs, estimated R&D costs/unit, and dealer markup at 6% are all included in the $87 estimate.

[e]Manufacturer markup of 20% was used by ERC.

[f]EPA did not provide specific estimate for ceramic fiber trap system; therefore, cost assumed to be the same as for ceramic monolith trap system.

[g]Dealer markup of 8% was used by ERC.

[h]Values reported by EPA in Ref. 8 are $259 to $389.

[i]Value reported by EPA in Reg. 8 is $57.00. Value used here is based on EPA estimate of two replacements of two sensors at $29 for parts and $28 for labor at each replacement.

[j]Value reported by EPA in Ref. 8 is $50.00. Value used here is based on EPA estimate of two maintenance events at $50 each.

[k]EPA does not consider trap replacement necessary.

[l]Trap replacement assumed at five years.

[m]Value reported by EPA in Ref. 8 is $34 (initial plus replacement cost). Value used here is based on a cost of $1.46/lb of catalyst. No labor costs for replacement or addition are included.

[n]Discounted exhaust pipe credit used as provided by EPA.

[o]Manufacturer trap costs range from $1285 to $2300.

TABLE 18 Adjusted EPA/ERC Cost Estimates (and Related Data) for Heavy Heavy-Duty Vehicles Using Ceramic Monolith Trap with Bypass/Burner Regeneration or Ceramic Fiber Trap with Catalytic Regeneration (all costs in 1984 $)

	Ceramic Monolith with Bypass/Burner		Ceramic Fiber with Catalyst Injection	
Cost Category	EPA	ERC	EPA	ERC
Vehicle GVW (lb)	26,000+	50,000	260,00+	50,000
Initial Cost to Manufacturer				
Trap	246.00	240.00	140.00	260.00
Container and Piping	46.00	120.00	--	120.00
Regeneration and Control System[a]	282.00	220.00	204.00	200.00
Modifications to Vehicle[b]	--	80.00	--	80.00
Total Component Cost	574.00	660.00	344.00	660.00
Assembly Labor @ $20/hr[c]	--	100.00	--	100.00
Assembly overhead @ 40%[c]	--	40.00	--	40.00
Total Cost to Manufacturer	574.00	800.00	344.00	800.00
Manufacturer Markup [d,e]	--	160.00	--	160.00
Estimated Tooling Costs/Unit[d]	--	50.00	--	50.00
Estimated R&D Costs/Unit[d]	87.00	150.00	87.00[f]	150.00
Increase in Dealer Costs	661.00	1160.00	431.00	1160.00
Dealer Markup at 8%[d,g]	--	92.80	--	92.80
User First Cost	661.00	1252.80	431.00	1252.80
Operating Data and Costs				
Vehicle Lifetime (mi)	520,000	520,000	520,000	520,000
Vehicle Lifetime (yr)	8	8	8	8
Maintenance Costs				
Per 100,000 miles	--	100	--	50.00
Discounted Lifetime Cost	114.03[h]	346.77	114.03[h]	173.39
Discounted Trap Maintenance Cost	100.03[i]	--	100.03[i]	--
Total Cost	214.06	346.77	214.06	173.39
Fuel Consumption				
Basic Fuel Economy (mpg)	7.0	6.44	7.0	6.44
Reduction Due to Trap (%)	1.0-1.5	2.0	0.5-1.0	0.75
Cost of Fuel ($/gal)	1.20	1.20	1.20	1.20
Discounted Lifetime Fuel Costs	600.47-900.7[j]	1318.69	300.24-600.47	488.28
Trap Replacement Costs[k]				
Trap Lifetime (mi)	--	250,000	--	150,000
Trap Replacements Needed	--	1	--	3
Trap Replacement Costs	--	776.00	--	816.00
Discounted Trap Replacement Costs	--	530.02	--	1692.32[l]

TABLE 18 (Cont'd)

Cost Category	Ceramic Monolith with Bypass/Burner EPA	Ceramic Monolith with Bypass/Burner ERC	Ceramic Fiber with Catalyst Injection EPA	Ceramic Fiber with Catalyst Injection ERC
Discounted Catalyst Replacement Costs @ 0.16 g/gal of Fuel Using 1% Penalty	--	--	25.77[m]	--
Discounted Exhaust Pipe Credit[n]	--	--	(81.00)	--
Total Operating Costs	814.53-1114.76	2195.48	459.07-1059.54	2353.99
Total Lifetime Costs[o]	1475.53-1775.76	3448.28	890.07-1490.54	3606.79

[a]EPA assumes periodic sparking in the fuel ignition system, resulting in unit cost savings of $7.00. EPA regeneration system costs include burner can, fuel delivery system, fuel ignition system, auxiliary air system, exhaust diversion system, and electronic control system. The individual costs of these items are shown in Table 8. For catalytic regeneration, catalyst dispensers and exhaust notifications replace some of these components.

[b]EPA assumes that vehicle modifications may be eliminated by using the 70% compliance clause; if a vehicle needs modification, EPA recommends that it be classified in the exempt 30% group.

[c]EPA does not include costs for assembly labor or overhead.

[d]EPA's manufacturer markup at 11%, tooling costs, estimated R&D costs/unit, and dealer markup at 6% are all included in the $87 estimate.

[e]Manufacturer markup of 20% was used by ERC.

[f]EPA did not provide specific estimate for ceramic fiber trap system; therefore, cost assumed to be the same as for ceramic monolith trap system.

[g]Dealer markup of 8% was used by ERC.

[h]Value reported by EPA in Ref. 8 is $71.00. Value used here is based on EPA estimate of three replacements of two sensors at $29 for parts and $28 for labor at each replacement.

[i]Value reported by EPA in Ref. 8 is $62.00. Value used here is based on EPA estimate of three maintenance events at $50 each.

[j]Values reported by EPA in Ref. 8 are $705 to $1058.

[k]EPA does not consider trap replacement necessary.

[l]Trap replacement assumed at two, four, and six years.

[m]Value reported by EPA in Ref. 8 is $104 (initial plus replacement cost). Value used here is based on a cost of $1.46/lb of catalyst. No labor cost for replacement or addition is included.

[n]Discounted exhaust pipe credit used as provided by EPA.

[o]Manufacturer trap costs range from $2810 to $4710 for a single trap and $3270 to $7210 for a dual trap.

TABLE 19 Adjusted EPA/ERC Cost Estimates (and Related Data) for Transit Buses Using Ceramic Monolith Trap with Bypass/Burner Regeneration or Ceramic Fiber Trap with Catalytic Regeneration (all costs in 1984 $)

	Ceramic Monolith with Bypass/Burner		Ceramic Fiber with Catalyst Injection	
Cost Category	EPA	ERC	EPA	ERC
Vehicle GVW (lb)	--	--	--	--
Initial Cost to Manufacturer				
Trap	132.00	150.00	106.00	170.00
Container and Piping	40.00	60.00	--	60.00
Regeneration and Control System[a]	276.00	180.00	175.00	160.00
Modifications to Vehicle[b]	--	100.00	--	100.00
Total Component Cost	448.00	490.00	281.00	490.00
Assembly Labor @ $20/hr[c]	--	80.00	--	80.00
Assembly overhead @ 40%[c]	--	32.00	--	32.00
Total Cost to Manufacturer	448.00	602.00	281.00	602.00
Manufacturer Markup @ 20%[d,e]	--	120.40	--	120.40
Estimated Tooling Costs/Unit[d]	--	100.00	--	100.00
Estimated R&D Costs/Unit[d]	87.00	300.00	87.00[f]	300.00
Increase in Dealer Costs	535.00	1122.40	368.00	1122.40
Dealer Markup at 8%[d,g]	--	89.79	--	89.79
User First Cost	535.00	1212.19	368.00	1212.19
Operating Data and Costs				
Vehicle Lifetime (mi)	540,000	540,000	540,000	540,000
Vehicle Lifetime (yr)	12	12	12	12
Maintenance Costs				
Per 100,000 Miles	--	70	--	40.00
Discounted Lifetime Cost	64.73[h]	214.63	64.73[h]	124.92
Discounted Trap Maintenance Cost	56.78[i]	--	56.78[i]	--
Total Cost	121.51	214.63	121.51	124.92
Fuel Consumption				
Basic Fuel Economy (mpg)	6.0	6.0	6.0	6.0
Reduction Due to Trap (%)	1.5	3.9	1.0	1.25
Cost of Fuel ($/gal)	1.00	1.00	1.00	1.00
Discounted Lifetime Fuel Costs	778.21[j]	2073.89	516.19	646.87
Trap Replacement Costs[k]				
Trap Lifetime (mi)	--	150,000	--	100,000
Trap Replacements Needed	--	3	--	5
Trap Replacement Costs	--	1428.00	--	516.00
Discounted Trap Replacement Costs	--	760.22[l]	--	1436.63[l]

TABLE 19 (Cont'd)

Cost Category	Ceramic Monolith with Bypass/Burner EPA	Ceramic Monolith with Bypass/Burner ERC	Ceramic Fiber with Catalyst Injection EPA	Ceramic Fiber with Catalyst Injection ERC
Discounted Catalyst Replacement Costs @ 0.16 g/gal of Fuel Using 1% Penalty	--	--	26.58[m]	--
Discounted Exhaust Pipe Credit[m]	--	--	(51.00)	--
Total Operating Costs	899.72	3048.74	613.28	2208.42
Total Lifetime Costs	1434.72	4260.93	981.28	3420.61

[a]EPA assumes periodic sparking in the fuel ignition system, resulting in unit cost savings of $7.00. EPA regeneration system costs include burner can, fuel delivery system, fuel ignition system, auxiliary air system, exhaust diversion system, and electronic control system. The individual costs of these items are shown in Table 8. For catalytic regeneration, catalyst dispensers and exhaust notifications replace some of these components.

[b]EPA did not address the costs of vehicle modifications for buses.

[c]EPA does not include costs for assembly labor or overhead.

[d]EPA's manufacturer markup at 11%, tooling costs, estimated R&D costs/unit, and dealer markup at 6% are all included in the $87 estimate.

[e]Manufacturer markup of 20% was used by ERC.

[f]EPA did not provide specific estimate for ceramic fiber trap system; therefore, cost assumed to be the same as for ceramic monolith trap system.

[g]Dealer markup of 8% was used by ERC.

[h]Value reported by EPA in Reg. 8 is $57.00. Value used here is based on EPA estimate of two replacements of two sensors at $29 for parts and $28 for labor at each replacement.

[i]Value reported by EPA in Ref. 8 is $50.00. Value used here is based on EPA estimate of two maintenance events at $50 each.

[j]Value reported by EPA in Ref. 8 is $1070.

[k]EPA does not consider trap replacement necessary.

[l]Trap replacement assumed at 3.5, 7, and 10.5 years for the ceramic monolith with bypass/burner generation and at 2.2, 4.4, 6.6, 8.8, and 11 years for the ceramic fiber trap with catalytic regeneration.

[m]Value reported by EPA in Ref. 8 is $34 (initial plus replacement cost). Value used here is based on value determined for medium truck.

[n]Discounted exhaust pipe credit used as provided by EPA.

TABLE 20 Adjusted EPA/ERC Life-Cycle Cost Estimates for Ceramic Monolith Trap with Bypass/Burner, by Vehicle Class

Vehicle Class	Estimated Total Vehicle Sales, 1983	Estimated Cost per Vehicle (1984 $)	
		EPA	ERC
2B	72,000	577-603	724
3	22,000	577-603	724
4	360	577-603	1,568
5	923	577-603	1,568
6	46,000	921-1,046	1,568
7	49,000	1,476-1,776	1,568
8	80,000	1,476-1,776	1,568-3,448
Buses	1,900	1,435	4,261
Total	272,000	--	--

replacement would be required in line-haul trucks and three in buses. The cost of these replacements represents 15% to 18% of the adjusted ERC estimates for trucks with the ceramic monolith trap. The number of replacements are even higher for ceramic fiber trap, and the associated costs represent 20% to 50% of the adjusted ERC estimates.

4. *The EPA's fuel economy allowance of 1% to 1.5% is in sharp contrast with ERC's 2.5% to 3.9%.* In a recent publication, tests with diesel engines indicate that the ERC figures may be more reliable, with penalities of 2.4% for line-haul vehicles and 3.9% for transit buses, particularly if the ceramic monolith trap with bypass/burner is utilized.

Overall, it appears that EPA estimates of the life-cycle costs of particular trap-oxidizer systems may represent the lowest possible figures; these costs, however, may be achieved if all of EPA's assumptions are valid. The adjusted ERC costs appear to be more reasonable, but may still err on the low side. At present, with the actual product lines not clearly defined for each specific application, it is somewhat premature to consider that any of these cost numbers are close to the actual commercial value. However, the values presented for the ceramic monolith system are probably less tenuous than those shown for the ceramic fiber system because the monolith system has been more extensively investigated. Further, we emphasize that most of the EPA and ERC cost derivations were based on data acquired with light-duty vehicles and on some engineering judgments. The actual cost figures for heavy-duty trucks may turn out to be quite different.

Still further, it appears that these cost estimates were developed by assuming that the per-vehicle costs of a trap-based 0.25-g/bph-hr standard would be no different than those of a 0.10-g/bph-hr standard. As discussed in Sec. 5.1, the EPA estimates of vehicle costs associated with the 0.10-g/bph-hr standard in 1994 simply represent an extension of the costs incurred by 60% of the HDDEs in 1991 to another 30% of those same vehicles in 1994. However, some manufacturers have argued that higher-efficiency traps would be required to meet this lower standard.[12] Moreover, to meet the 0.1-g/bph-hr standard in 1994, trap-oxidizer systems would be required on the most difficult engine applications that were previously avoided under the 0.25-g/bhp-hr standard. Both of these factors could result in more expensive traps than estimated above. While EPA argues that the engineering experience gained with the 1991 standard and the long lead time for the 1994 standard of 0.1 g/bhp-hr might actually result in a less costly trap-oxidizer system, it is not at all clear that the costs presented in this analysis accurately reflect the costs of the 0.1-g/bhp-hr standard.

One final point: this comparative cost analysis has assumed that truck operators will replace trap-oxidizer systems as needed (only ERC makes this assumption, because EPA assumes the systems will not need replacement) and will bear the fuel economy penalty associated with these systems. However, the potential for tampering (disconnecting the trap systems) is great. While tampering is generally illegal and may result in civil penalties, emissions enforcement for HDVs is currently minimal. The EPA enforces the tampering provisions through surveillance, investigation, and prosecution, but to date the focus of its tampering program has been on light-duty vehicles.[24] At the state level, heavy-duty vehicles are presently excluded from many inspection-maintenance programs.[25] Unless enforcement is strengthened, tampering to avoid the considerable operating and maintenance costs associated with particulate trap-oxidizer systems may be extensive.

REFERENCES

1. Saricks, C.L., and M.K. Singh, *Effectiveness, Benefits, and Costs of More Stringent Nitrogen Oxide and Particulate Emission Controls for Heavy Duty Trucks*, Argonne National Laboratory Report ANL/EES-TM-273 (Nov. 1984).

2. *Draft Regulatory Analysis, Environmental Impact Statement and NO_x Pollutant Specific Study for Proposed Gaseous Emission Regulations for 1985 and Later Model Year Light-Duty Trucks and 1986 and Later Model Year Heavy-Duty Engines*, Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Washington, D.C. (Nov. 5, 1980).

3. *Control of Air Pollution from New Motor Vehicles and New Motor Vehicle Engines: Particulate Regulation for Heavy-Duty Diesel Engines (Notice of Proposed Rulemaking)*, U.S. Environmental Protection Agency, 46 Federal Reg. 1910 (Jan. 7, 1981).

4. *Response to EPA Advance Notice of Proposed Rulemaking for Gaseous Emissions Regulations for 1985 and Later Model Year Light-Duty Trucks and 1986 and Later Model Year Heavy-Duty Engines and EPA Notice of Proposed Rulemaking for Particulate Regulations for Heavy-Duty Diesel Engines*, Caterpillar Tractor Co. (Sept. 9, 1982).

5. General Motors Submittal to U.S. Environmental Protection Agency Public Dockets A-80-31 and A-80-18 (Sept. 13, 1982).

6. *Diesel Particulate Study*, Standards Development and Support Branch, Emission Control Technology Division, Office of Mobile Sources, Office of Air and Radiation, U.S. Environmental Protection Agency (Oct. 1983).

7. *Draft Regulatory Impact Analysis and Oxides of Nitrogen Pollutant Specific Study*, Office of Air and Radiation, Office of Mobile Sources, U.S. Environmental Protection Agency (Fall 1984).

8. *Regulatory Impact Analysis, Oxides of Nitrogen Pollutant Specific Study and Summary and Analysis of Comments*, Office of Air and Radiation, Office of Mobile Sources, U.S. Environmental Protection Agency (March 1985).

9. Weaver, C.S., C. Miller, and L. Nelowel, *Particulate Control Technology and Particulate Emissions Standards for Heavy-Duty Diesel Engines*, prepared by Energy and Resource Consultants, Inc., for U.S. Environmental Protection Agency (Dec. 1984).

10. *Control of Air Pollution from New Motor Vehicles and New Motor Vehicle Engines: Gaseous Emission Regulations for 1985 and Later Model Year Light-Duty Trucks, Gaseous and Evaporative Emission Regulations for 1985 and Later Model Year Heavy-Duty Engines, and Emission Regulations for 1978 and Later Model Year

Motorcycles (Final Rule), U.S. Environmental Protection Agency, 48 Federal Reg. 52, 170 (Nov. 16, 1983).

11. *Control of Air Pollution from New Motor Vehicle Engines: Gaseous Emission Regulations for 1987 and Later Model Year Light-Duty Vehicles, Light-Duty Trucks, and Heavy-Duty Engines; Particulate Emission Regulations for 1987 and Later Model Year Heavy-Duty Diesel Engines (Proposed Rule),* U.S. Environmental Protection Agency, 49 Federal Reg. 40, 258 (Oct. 15, 1984).

12. *Control of Air Pollution from New Motor Vehicle Engines; Gaseous Emission and Particulate Emission Regulations (Final Rule),* U.S. Environmental Protection Agency, 50 Federal Reg. 10606 (March 15, 1985).

13. U.S. Environmental Protection Agency Public Docket A-80-18 (Dec. 1984).

14. Brown, K.M., Ford Motor Co., personal communication (Sept. 1985).

15. *Draft Regulatory Analysis: Heavy-Duty Diesel Particulate Regulations,* U.S. Environmental Protection Agency (Dec. 1980).

16. *Cost of Selected Trap-Oxidizer System Components for Heavy-Duty Vehicles,* prepared by Jack Faucett Associates and Mueller Associates for U.S. Environmental Protection Agency (Sept. 1984).

17. *Cost of Selected Heavy-Duty Diesel Engine Emission Control Components,* prepared by Jack Faucett Associates and Mueller Associates for U.S. Environmental Protection Agency (Feb. 1985).

18. *Cost Estimations for Emission Control Related Components/Systems and Cost Methodology Description,* prepared by Rath and Strong, Inc., for U.S. Environmental Protection Agency, EPA-460/3-78-002 (March 1978).

19. *Heavy-Duty Vehicle Emission Conversion Factors 1962-1997,* Mahlon C. Smith IV, U.S. Environmental Protection Agency, EPA-AA-SDSB-81-1 (Aug. 1984).

20. *EPA's Retail Price Equivalency Methodology,* Report from Putnam, Hayes and Bartlett, Inc. to Will Smith, Economic Analysis Division, U.S. Environmental Protection Agency (Sept. 1984).

21. *Historical and Projected Emission Conversion Factors and Fuel Economy for Heavy-Duty Trucks 1962-2002,* Energy and Environmental Analysis, Arlington, Va., (1983).

22. *New Truck Sales by Make and GVW Class,* Automotive News (June 24, 1985).

23. *Diesel Particulate Control,* SAE Publication P-158 (Feb. 1985).

24. Greco, R., U.S. Environmental Protection Agency, personal communication (Feb. 1986).

25. Cabaniss, J.M., *Overview of I/M Activities and Issues,* in Mobile Source Issues in the 1980s, Proc. Air Pollution Control Association Specialty Conf. (Feb. 1984).

APPENDIX

LIST OF ABBREVIATIONS

CAA	Clean Air Act
CO	Carbon monoxide
EPA	U.S. Environmental Protection Agency
ERC	Energy and Resource Consultants, Inc.
g/bhp-hr	Gram/brake horsepower-hour
GM	General Motors
GVW	Gross vehicle weight
HC	Hydrocarbon
HDDE	Heavy-duty diesel engine
HDDT	Heavy-duty diesel truck
HDDV	Heavy-duty diesel vehicle
HDT	Heavy-duty truck
HDV	Heavy-duty vehicle
HDGE	Heavy-duty gasoline engine
hp	Horsepower
L	Liter
lb	Pound
LDDT	Light-duty diesel truck
LDDV	Light-duty diesel vehicle
LDT	Light-duty truck
LDV	Light-duty vehicle
MVMA	Motor Vehicle Manufacturers Association
NO_x	Oxides of nitrogen (in general, nitric oxide and nitrogen dioxide)
NPRM	Notice of Proposed Rulemaking
R&D	Research and development
RIA	Regulatory Impact Analysis
RPE	Retail price equivalent
SwRI	Southwest Research Institute
VW	Volkswagen